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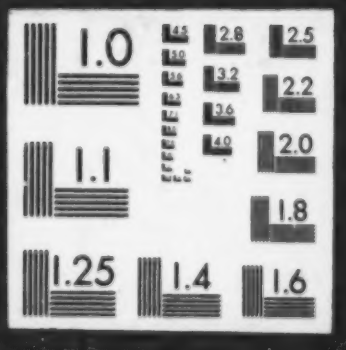

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TRACING POLLUTED RESERVOIR INFLOWS WITH FLUORESCENT DYES

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Vanderbilt University
Nashville, Tennessee

May 1969

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TRACING POLLUTED RESERVOIR INFLOWS WITH FLUORESCENT DYES

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Technical Report No. 18

Department of Environmental and Water Resources Engineering
Vanderbilt University
Nashville, Tennessee

May, 1969

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BACKGROUND

Effects of Impoundments on Water Quality

On considering several distinct water quality parameters impoundments may have either beneficial or detrimental effects on downstream water quality. Briefly, the beneficial effects include the following:

1. Smoothing the water temperature fluctuations over a yearly cycle,
2. Reducing turbidity,
3. Bleaching color,
4. Smoothing other natural or man-made fluctuations in water quality.

And the detrimental effects would include the following (2, 3, 11, 13, 21, 25):

1. Increasing materials leached or exchanged from bottom sediments, particularly iron and manganese,
2. Reducing dissolved oxygen,
3. Reducing pH,
4. Promoting aquatic growths or biological degradation which increase taste, odor, or color-producing substances,
5. Increasing water temperature near the surface of the impoundment.

All of these effects may be affected greatly by the residence time of water in the reservoir, the length of contact time with certain portions of the boundaries, the degree of vertical stratification and mixing, the mixing or dilutional effects taking place, and the general flow patterns and operational characteristics of the reservoir.

INTRODUCTION

Statement of the Subject

Due to the rapidly expanding population and industrialization, the need for wise environmental pollution control and water resources management is critical. This need has been recognized by the public, and enormous, cooperative efforts in this direction have been initiated by the concerned governmental agencies, industries, and technical organizations. Through this effort, much useful scientific knowledge has been acquired, and it is now being applied in the pollution control and resources management programs. There is not enough information at this time for engineers to make consistent and accurate predictions of water quality, and, therefore, the effectiveness and economical efficiency of these programs is lessened. In particular, knowledge of the effects of reservoirs and storage impoundments is urgently required.

The flow patterns and mixing, or dispersing, characteristics of storage impoundments must be investigated to determine the effects of the reservoirs on water quality and to determine the methods of operating, or controlling, the reservoirs to produce the highest water quality. The most promising methods for studying the mixing characteristics and flow patterns of reservoirs entails the use of a conservative or semi-conservative tracer. Furthermore, the fluorescent tracers appear to be the most practical for these studies. It was the purpose of this investigation to demonstrate the usefulness of these tracers.

Scope of the Investigation

This investigation was performed to demonstrate the use of Rhodamine B, a fluorescent dye, as a tracer for studying the flow patterns of polluted water and the mixing regimes of a large storage impoundment, and to relate the information to conditions in the impoundment. To accomplish this, the characteristics of the dye and detection instrumentation, and the characteristics of the impoundment were considered in detail.

Study Site

Cherokee Reservoir, a large Tennessee Valley Authority (TVA) impoundment on the Holston River, was chosen for the studies because it has had a history of most of the classical problems in water quality associated with storage impoundments, particularly manganese. Welsh(24) describes the additional problem of eutrophication inside the reservoir and the nuisance problem of floating macrophytes in the Holston River inflow.

It is downstream from the Kingsport, Tennessee, industrial area and is probably the most polluted of the TVA reservoirs. TVA plans a comprehensive water quality study for the reservoir during 1969, and this study was designed to furnish preliminary knowledge of flow patterns and detention times so that the comprehensive study might be conducted more efficiently. It is hoped that the long-range result of the comprehensive study will be modification of operating procedure of the reservoir system to improve water quality.

Cherokee Reservoir was built in 1941 by the TVA for navigation, flood control, power generation, and recreation. The impoundment is located between Holston River Mile (HRM) 52 and HRM 111, or about 30 miles Northeast of Knoxville, Tennessee. It is one of the largest storage impoundments in the TVA system, with a maximum volume of 1,570,000 acre-feet, a surface area of 31,100 acres, a length of 59 miles, and a depth at the dam of about 150 feet, with an elevation at the top of the gates of 1075 feet above mean sea level (AMSL).

A map of the reservoir is shown in Figure 1. The inflow to the Cherokee Reservoir is from the unregulated North Fork Holston River and the South Fork Holston River with a regulation complex including Fort Patrick Henry, Boone, South Holston, Wilbur, and Watauga Dams. The inflow patterns are smoothed somewhat by the small detention dam and cooling water flow at TVA's John Sevier Steam Plant located at HRM 106.3. The outflow is typical of that associated with primarily peaking power and flood control operation with a minimum base flow provided for the downstream users (2, 25).

Plan of Development

This investigation is reported as follows:

1. Background information
2. Equipment and Methodology
3. Results
4. Discussion and conclusions

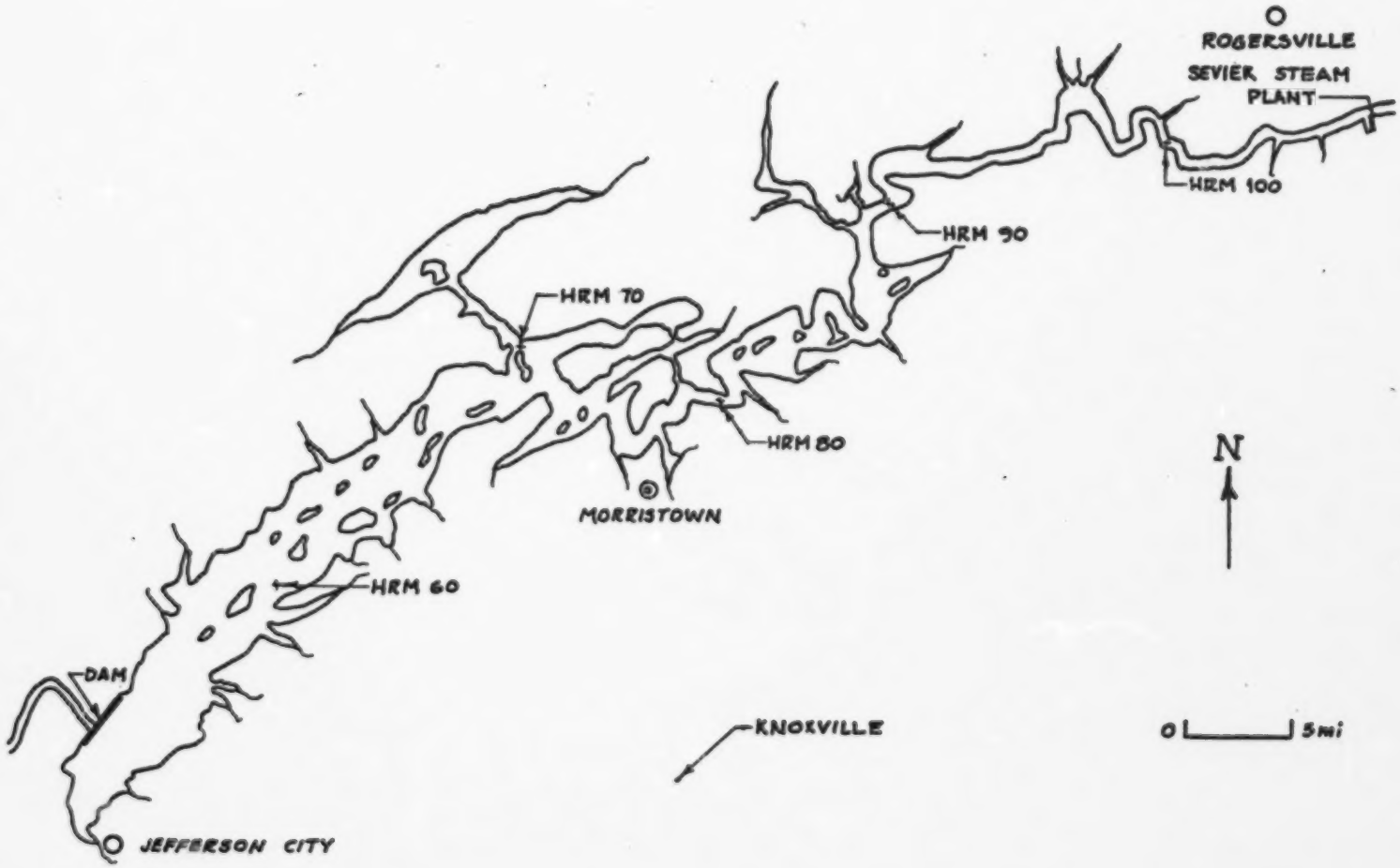


FIGURE 1 - CHEROKEE RESERVOIR

Flow Patterns

In general, the inflow to an impoundment seeks a level in the impoundment which has an equal density. The density of the incoming water is determined by its temperature and dissolved or suspended solids concentration. Depending on the level in the reservoir, the flow is designated an under-, inter-, or overflow.

Brooks (1) and others have proposed analytical solutions to various types of withdrawals from density stratified reservoirs. However, Jaske (12) has shown that actual withdrawal patterns often do not agree with the withdrawal solutions because the boundaries and operating conditions in the real reservoirs may be different and much more complex than those assumed for the analytical solution.

The form of the flow regime has a great effect on the vertical eddy diffusivity, and this heightens the complexity of reservoir analysis (10).

Fluorescent Tracers

Previous Uses of Tracers

Fluorescent tracers have recently been used for studying rivers (16), estuaries (8), and impoundments (25) with varying degrees of success. These dyes approach ideal tracers, and they are rapidly supplanting other materials such as salts and radioactive isotopes for use as tracers.

An ideal material for tracers in water is considered to have the following properties. First, it is conservative or, at least, degradable in a known fashion. Second, it is easily and accurately detectable

in low concentrations. Third, it is completely miscible or dissolved in water. Fourth, it must not be physiologically harmful to the ecology of the water body or to the humans drinking the water, and it must not af fect machinery or industrial processes using the water. And Finally, it should be aesthetically unoffensive; that is, it should not have an unusual color, odor, or taste.

All three major groups of tracer materials -- salts, radioisotopes, and fluorescent dyes, have shortcomings when compared with an ideal tracer material. However, the fluorescent dyes are becoming recognized as the superior material by these standards. Salts are used infrequently because, generally, a large concentration is necessary for detection. For example, a chloride concentration of about 100 mg/l to 200 mg/l is required for environmental studies (2). This is inconvenient due to the large mass of salt required, and unwanted because chlorides of about 250 mg/l may taste salty (5). Radioisotopes are excellent tracers since they decay in a predictable fashion and since they are detectable in small concentrations although expensive equipment is required. However, they have the obvious and serious drawback of being harmful to those using the water for drinking (9,20). However, in the concentration used the main danger is to the handlers.

With the recent advances in fluorometry, fluorescent dyes are becoming the preferred tracer material with the only serious drawback being a characteristic color above very low concentrations. The dyes which have been used as tracers are fluoroscein, pontacyl brilliant pink B, rhodamine B, and, more recently, rhodamine WT. Other fluorescing substances have not been used for various reasons, the most common

reason being that they are excited by ultraviolet light, and therefore they must compete with fluorescing materials commonly found in water (19).

All of these dyes possess some undesirable characteristics. Fluorescein is unsuitable for most purposes since it is easily degraded by photochemical and bacterial action. Rhodamine B is adsorbed by suspended solids to a greater degree than the other remaining dyes, and Pontacyl Brilliant Pink B is relatively more expensive, while the newer Rhodamine WT appears to be the most promising at this time (6,19).

Dye Characteristics

Rhodamine B, Rhodamine WT, and Pontacyl Brilliant Pink B are chemically related xanthene dyes which have, in addition to their ultraviolet adsorption peaks, strong absorptions at 550 mμ, 556 mμ, and 560 mμ, and corresponding fluorescence peaks at 570 mμ, 580 mμ, and 578 mμ, respectively. All three dyes are unaffected by pH between 5 and 10. They are resistant to photochemical decay, and they have similar minimum detectable concentrations. In a 16 hour determination of adsorption by suspended sediments, 41% of the Rhodamine B, 6% of the Rhodamine WT, and 5% of the Pontacyl Brilliant Pink B was adsorbed. Moreover, the fluorescence of the dyes is temperature dependent, and the relationship is expressed by the equation

$$F_r = F_s \exp\left[n(T_r - T_s)\right] \qquad (1)$$

where F_r = the calculated fluorescence of a sample at the reference temperature, T_r; F_s = the fluorescence of the sample at the sample temperature, T_s; and n = the temperature coefficient having values of

$-0.027°C^{-1}$, $-0.026°C^{-1}$, and $-0.029°C^{-1}$ for Rhodamine B, Rhodamine WT, and Pontacyl Brilliant Pink B, respectively (6, 19).

Information from Tracer Studies

Much about impoundments can be learned from tracer studies, and much can be learned only from tracer studies. The patterns of flow and mixing in impoundments are extremely complex due to geometry, the local variations in meterological conditions, natural runoffs and inflows, and variable operational procedures. These patterns are needed to determine the heat and gas transfer mechanisms, and the pollutant and solid diffusion porcesses occuring in the impoundment. In other words, knowledge about the flow and mixing regimes in an impoundment can be used to predict the effect of the impoundment on water quality.

The phenomena considered in this report are vertical diffusivity, longitudinal dispersion, stability of stratification, and flow patterns and their relationship to water quality.

Vertical Diffusion

Orlob (18) draws the following general conclusions concerning the value of the vertical eddy diffusivity in reservoirs:

> "1. Effective mixing in the epilimnion is greatest near the surface but declines rapidly with depth as the thermocline is approached.
>
> 2. The effective diffusion coefficient is minimal at or very near the position of the maximum temperature gradient, the so-called 'thermocline.'
>
> 3. In the hypolimnion the effective diffusion coefficient increases with depth in a more or less erratic manner, reaching a maximum roughly equivalent to that of the epilimnion at about mid-depth, thereafter decreasing as the bottom is approached."

Typical values of the vertical eddy diffusivity as determined by Orlob are given in Figure 2 and Table 1. Moreover, the vertical eddy diffusivity is unique to the hydrologic and energy regime with which it is associated. Therefore, the coefficient for a given lake can be determined only by actual measurement until, or unless, the relationships between the coefficient and the environment are better understood. Hutchinson (10) gives some insight into the effects of winds, internal currents, and seiches on the variations of the vertical eddy diffusivity.

Stability of Stratification

Keulegan (15) has suggested a parameter θ as a desired criterion for determining whether a stratified flow is stable or whether mixing will take place, where θ is

$$\theta = (V_2 g \Delta\rho/\rho_1)^{1/3}/U \qquad (2)$$

where V_2 = the kinematic viscosity of the water in the lower layer; $\Delta\rho$ = the difference in density between the two stratified layers; ρ_1 = the density of the upper layer; and U = the average velocity difference between the two layers. According to Keulegan, the two layers will be unstable and will, therefore, mix if θ is less than the following:

$$\theta = 0.127, \text{ for } Re<450 \qquad (3)$$

$$\theta = 0.178, \text{ for } Re>450 \qquad (4)$$

where Re is the Reynolds number.

Longitudinal Dispersion

The one-dimensional continuity equation for a pollutant or tracer in water can be written

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - \bar{U} \frac{\partial C}{\partial x} \qquad (5)$$

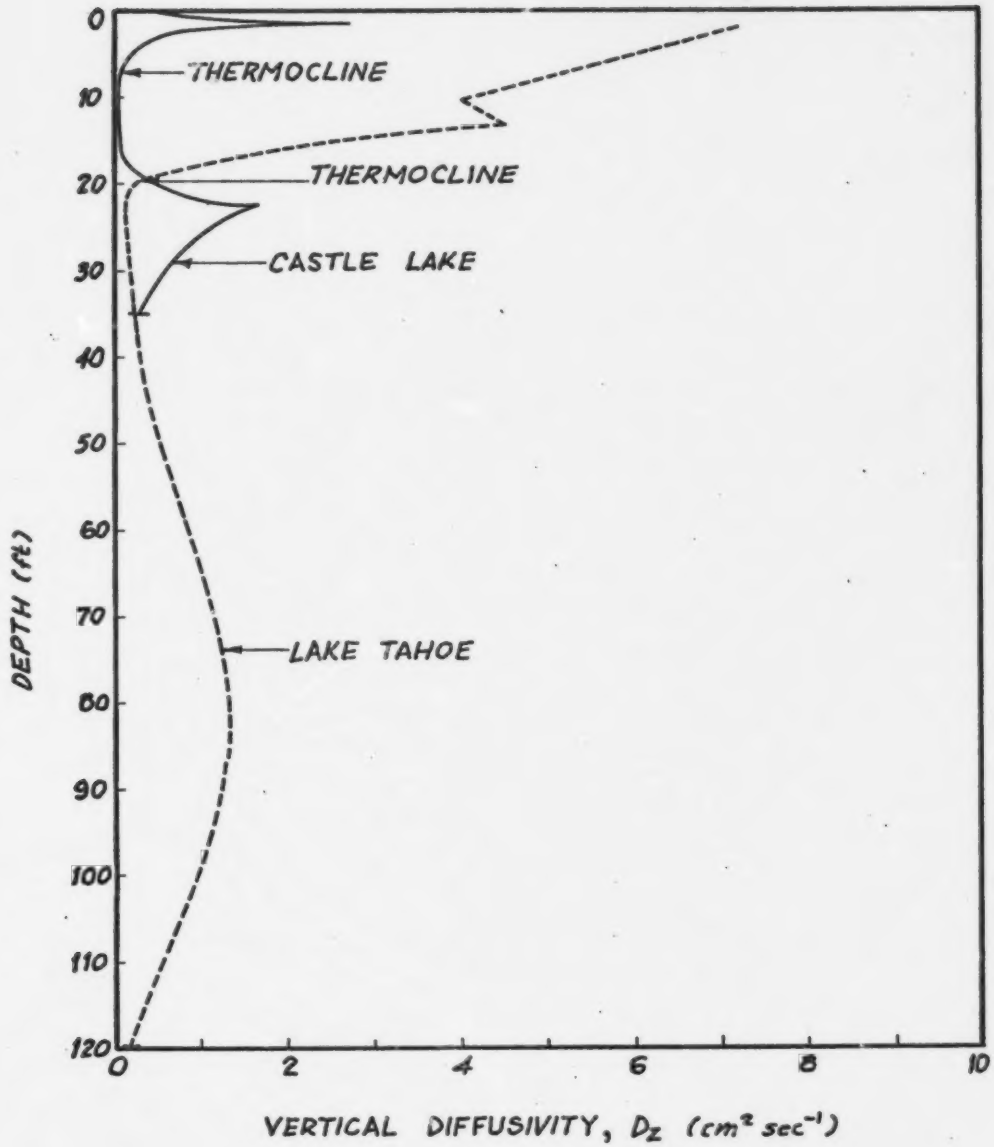


FIGURE 2 - TYPICAL VERTICAL DIFFUSIVITY PROFILES (AFTER ORLOB)

TABLE I

ENERGY DISTRIBUTION AND MIXING PROPERTIES OF
FOUR THERMALLY STRATIFIED IMPOUNDMENTS (AFTER ORLOB)

IMPOUNDMENT	WATER DEPTH	TEMPERATURE PROFILE	EFFECTIVE DIFFUSION COEFFICIENT* cm^2/sec
Fontana Reservoir	65 m	22.2°C @ Surface	0.81 @ Surface
		18.5°C @ 4.5m (thermocline)	0.17 @ thermocline
		6.9°C @ 54m (outlet)	1.15 @ 28.5 m
Hungry Horse Res.	103.5m	19.4°C @ Surface	3.7 @ Surface
		13.9°C @ 9.1m (thermocline)	0.12 @ thermocline
		4.0°C @ 103.5m (bottom)	1.7 @ 54m
Lake Tahoe	490 m	14.7°C @ Surface	9.2 @ Surface
		12.8°C @ 19.5m (thermocline)	0.10 @ thermocline
		5.4°C @ 120 m	1.2 @ 90 m
Castle Lake	35 m	19.2°C @ Surface	2.6 @ 3m
		14.5°C @ 6.5m (thermocline)	0.02 @ thermocline
		4.5°C @ 35m (bottom)	1.5 @ 22 m

*Note: Computed values recorded for the effective diffusion coefficient are respectively, the maximum determined for the epilimnion, the minimum in the region of the thermocline, and the maximum in the hypolimnion.

where C = the average cross-sectional concentration of the pollutant; x = the coordinate in the direction of the mean flow; $\bar{u}$ = the mean velocity of the flow; and D_L = the longitudinal dispersion or mixing coefficient. A solution of the continuity equation describing the variation in concentrations of the pollutant in time and space for an impulse injection is

$$C = \frac{M}{A\sqrt{2\pi D_L t}} \exp\left[- \frac{(x - \bar{u}t)^2}{4 D_L t} \right] \qquad (6)$$

where M = the total mass of the pollutant; A = the cross-sectional area of flow normal of x. This solution can then be transformed into the simplified form

$$\frac{C}{M/A\bar{u}} = \sqrt{\frac{Pe}{4\pi t \cdot t_{ave}}} \exp\left[- \frac{Pe(1 - t/t_{ave})^2}{4t / t_{ave}} \right] \qquad (7)$$

where $M/A\bar{u}$ = the area under the curve; t_{ave} = the mean residence time, $x/\bar{u}$; and Pe = the Peclet Number, $\bar{u}x/D_L$.

The values of the parameters Pe and t_{ave} in the reduced form of the solution to the continuity equation can be determined from the observed data by a least-squares regression program as described by Thackston (23). The values of D_L can then be found from Pe. Also, D_L can be determined by the change in variance of the tracer cloud from the familiar Einstein relationship

$$D_L = \frac{\bar{u}^2}{2} \frac{\partial(\sigma_t^2)}{\partial t} \qquad (8)$$

This solution of the continuity equation is not strictly applicable to storage impoundments since the assumption of uniform, steady flow is invalid. However, the values determined for the parameters in the continuity equation using the given solution should be valid for a particular reservoir and other reservoirs with similar geometry and operational patterns.

METHODOLOGY AND EQUIPMENT

Fluorescent Dye and Detection Equipment

Rhodamine B was chosen as the tracer material for this study due to its availability and generally good detection characteristics and measures were taken during the calibration to reduce any inaccuracies caused by adsorption. The dye was purchased in 55-gallon drums as a 40 percent dilution in glacial acetic acid.

The detection system was designed to use an Aminco Fluoro-Microphotometer (Model 4-7102) which was converted for flow-through fluorometry by adding a 150 mm o.d. flow-through cuvette. A 12-volt Jaske Water Puppy was used to pump water from 50-foot sections of smooth plastic garden hose which was mounted on a garden hose reel to the fluorometer. A plastic diffuser and screen was mounted on the last section of hose so that the water being pumped through the hose would be primarily from the level of the diffuser. The a.c. power for the fluorometer was provided by a storage battery and a Powercon inverter, which was found to be very stable and to produce approximate sine wave voltage.

This equipment was mounted in a 17-foot boat which was equipped with a 75-hp outboard engine with an electric starter and generator. The fluorometer was protected by an aluminum foil tent. The boat's generator was found to provide sufficient power to properly operate the detection system without additionally recharging the batteries. A diagram of the sampling system is shown in Figure 3.

The fluorometer was equipped with a green lamp (Aminco No. 4-7156), which provides continuous spectra from 520 mμ to 560 mμ. The primary

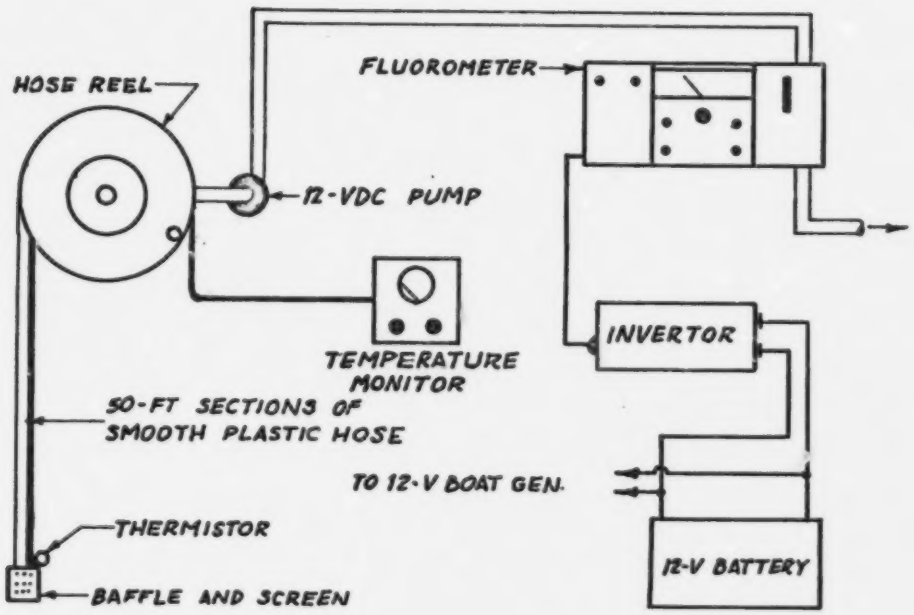


FIGURE 3 · EQUIPMENT DIAGRAM

filter was a composite of a Wratten No. 77A and a No. 64 filter which has an effective band-pass spectrum of 510 mμ to 565 mμ. The secondary filter was a Wratten No. 23A which has a sharp cutoff of spectra below 570 mμ. The band-passes of the filters is illustrated in Figure 4 (14).

Calibration and Operation of Equipment

A stock solution of dye was prepared by diluting a carefully weighed amount of dye with distilled water so that 1 ml of stock solution would produce a concentration of 1 μg/l in the 15-liter calibration vessel. This stock solution was carried to the field so that the fluorometer could be calibrated under actual working conditions. The dilution water was prepared by mixing equal amounts of lake water from the depths to be sampled. This was necessary because of a difference in background with depth and will be explained later.

Fifteen liters of the dilution water was placed in a carboy in the boat, and the fluorometer was allowed to warm up. Next, a volume of stock solution was pipetted into the carboy and mixed for about 15 min before the water was circulated through the fluorometer. This was found to be necessary to allow adsorption of the dye onto the suspended sediments to occur, thus yielding a calibration approximately corrected for adsorption. At each determination, the water temperature was recorded so that the calibration could be corrected for the temperature effects previously explained. Each point on the calibration curve was determined in the same manner with the maximum concentration being 100 μg/l. Since the calibration was linear over increments of 10 μg/l to 25 μg/l, the number of points required in each range was determined accordingly.

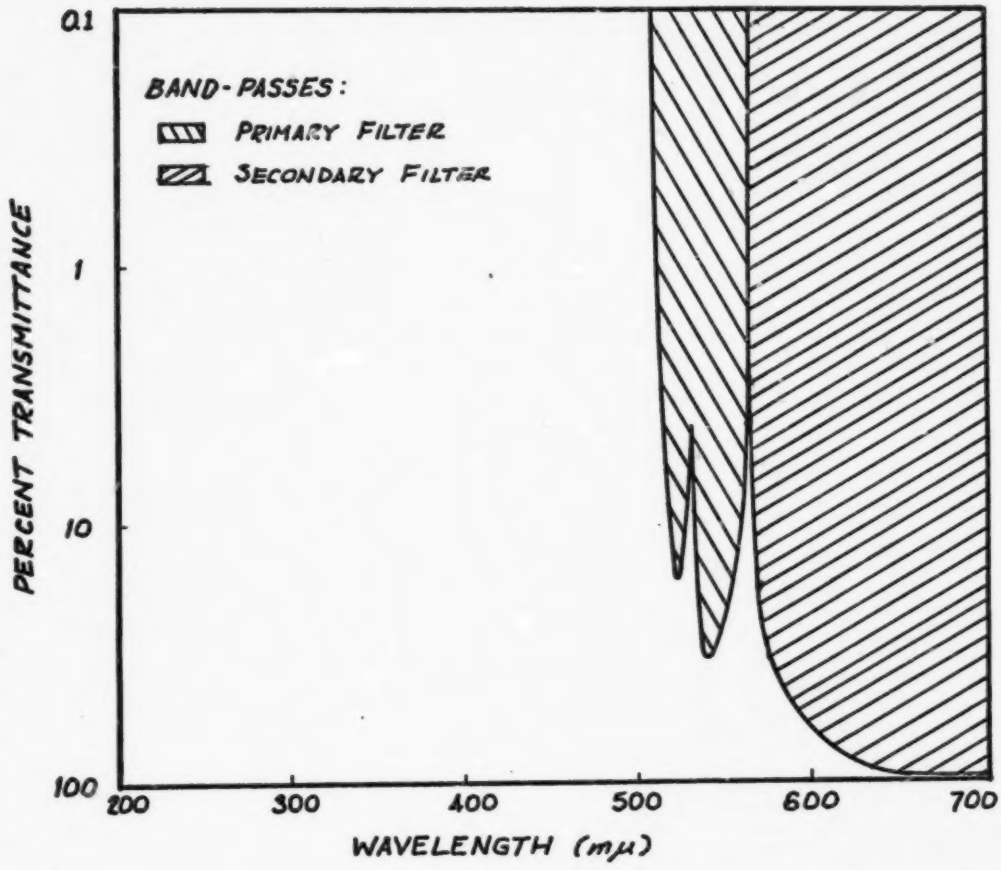


FIGURE 4 - FILTER BAND-PASSES

The fluorometer was calibrated daily at the beginning of the studies, as shown in Figure 5. However, it was decided to recalibrate only every three days after it became evident that there were only insignificant changes in the daily calibrations. In other words, there was excellent reproducibility in calibrating the fluorometer, and much time was saved by not calibrating daily.

It was found that there were no significant water temperature changes in passage through the hose and fluorometer, and the detention time in the hose was determined to be only about 20 seconds per 50 feet of hose.

Determination of Background

It was found that the background in impoundments must be carefully determined when working with dye concentrations less than approximately 10 μg/l since the background in the test reservoir varied vertically by an amount equivalent to about 0.5 μg/l as shown in Figure 6. This was thought to be caused by the change in suspended solids due to depth, since there is some overlap in the combined spectra of the primary and secondary filters of the fluorometer. This view is strengthened since Hutchinson (10) reports that generally there is a vertical variation in scattered light detected by nepthelometry on stratified water bodies. It is also reasonable to assume that some of this variation is due to the background fluorescence of algae and other materials. However, attempts to show this relationship were unsuccessful. Another problem concerned with background was the fact that it changed slightly from reach to reach and with time in a given reach. This problem was handled in what is thought to be a satisfactory manner by determining the background as many times as possible and subjectively fitting curves to the data.

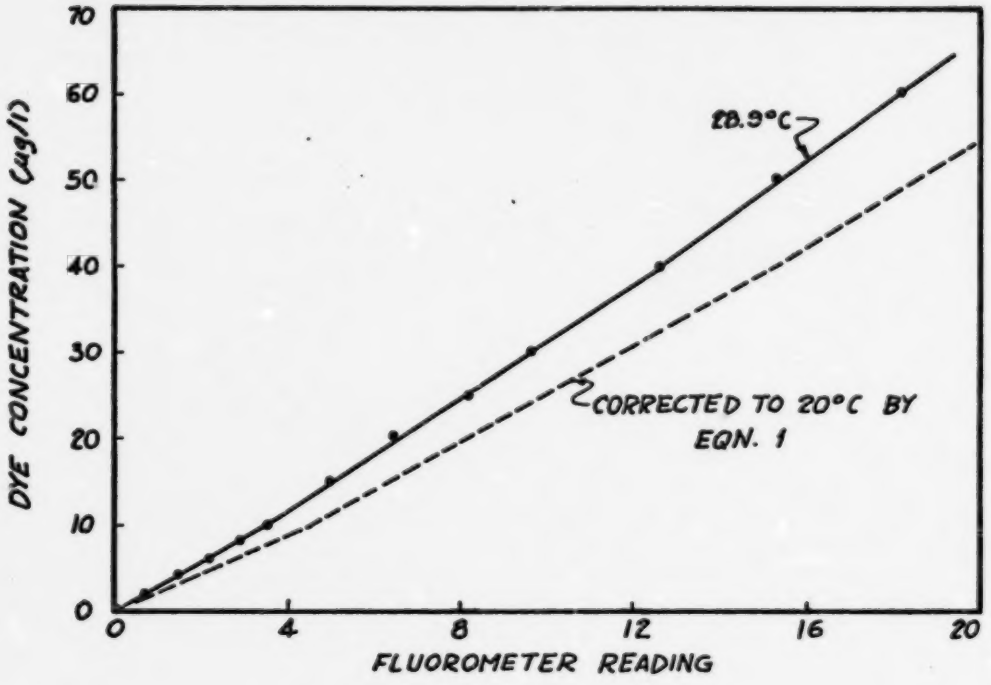


FIGURE 5 - TYPICAL CALIBRATION CURVE

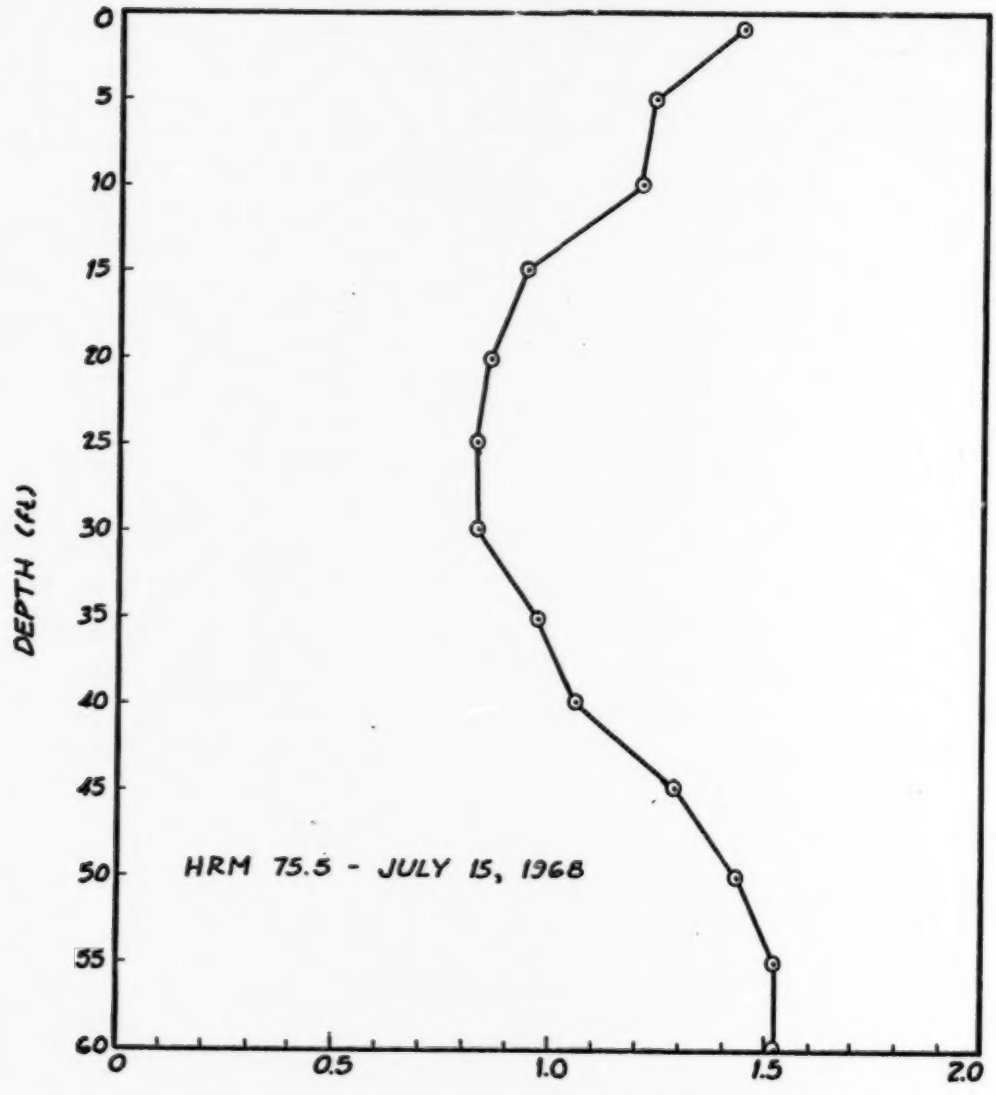


FIGURE 6 - TYPICAL BACKGROUND FLUORESENCE PROFILE

Dye Injection

The spillway of the detention dam for the John Sevier Steam Plant cooling water pond was selected as the dye injection point because the turbulence below the spillway provided excellent initial mixing. The steam plant is located at Holston River Mile (HRM) 106.3. The plant has four generators rated at 200 megawatts, each requiring about 250 cfs of condensing water per unit. At the time of the infections, two units were in operation and the discharge canal flowrate was about 500 cfs.

The flow in the Holston River at the steam plant has two primary components during the spring and summer -- the warmer, nearly constant flow from the North Fork Holston and the colder, pulsating flow from Fort Patrick Henry on the South Fork Holston. During the dye injections, the flowrate from the North Fork was about 500 to 700 cfs; the flowrate from the South Fork varied daily from no flow to an eight-hour flow that averaged from 5000 cfs to 10,000 cfs during the week and as little as a few hundred cubic feet per second during the weekend. Graphs of average daily inflows and outflows are shown in Figures 7 and 8. These pulses require 16 to 18 hours to reach the steam plant and about 20 hours to reach the TVA recording temperature gage at HRM 104.5. The temperatures of the two flows differed by as much as 5° to 10°C during the summer as depicted in Figure 9.

Two separate dye injections were performed. The first injection was designed to tag the cold water pulse from the South Fork Holston on June 14, 1968. Five hundred and forty pounds of dye-acetic acid solution, or 216 pounds of pure dye, was injected by gravity into the spillway at a constant rate for a 6-hour period beginning at 8:30 AM and

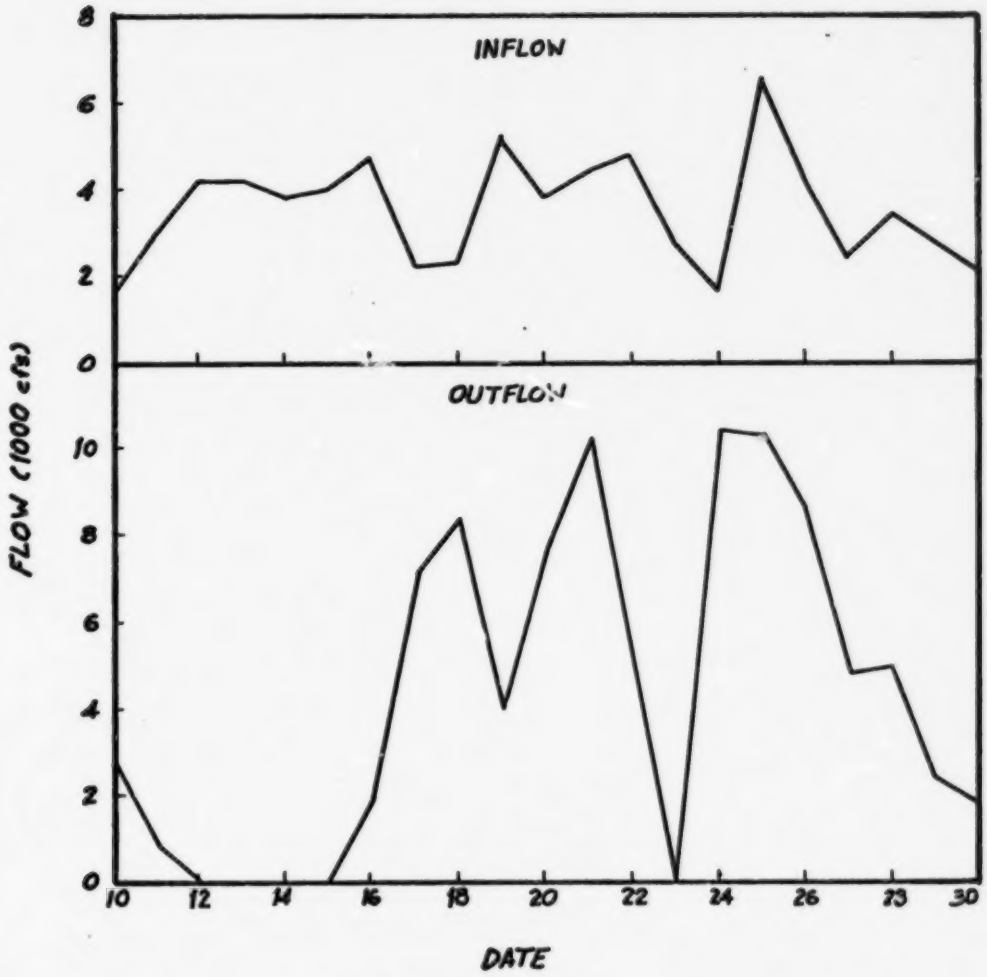


FIGURE 7 - FLOWRATES FOR JUNE

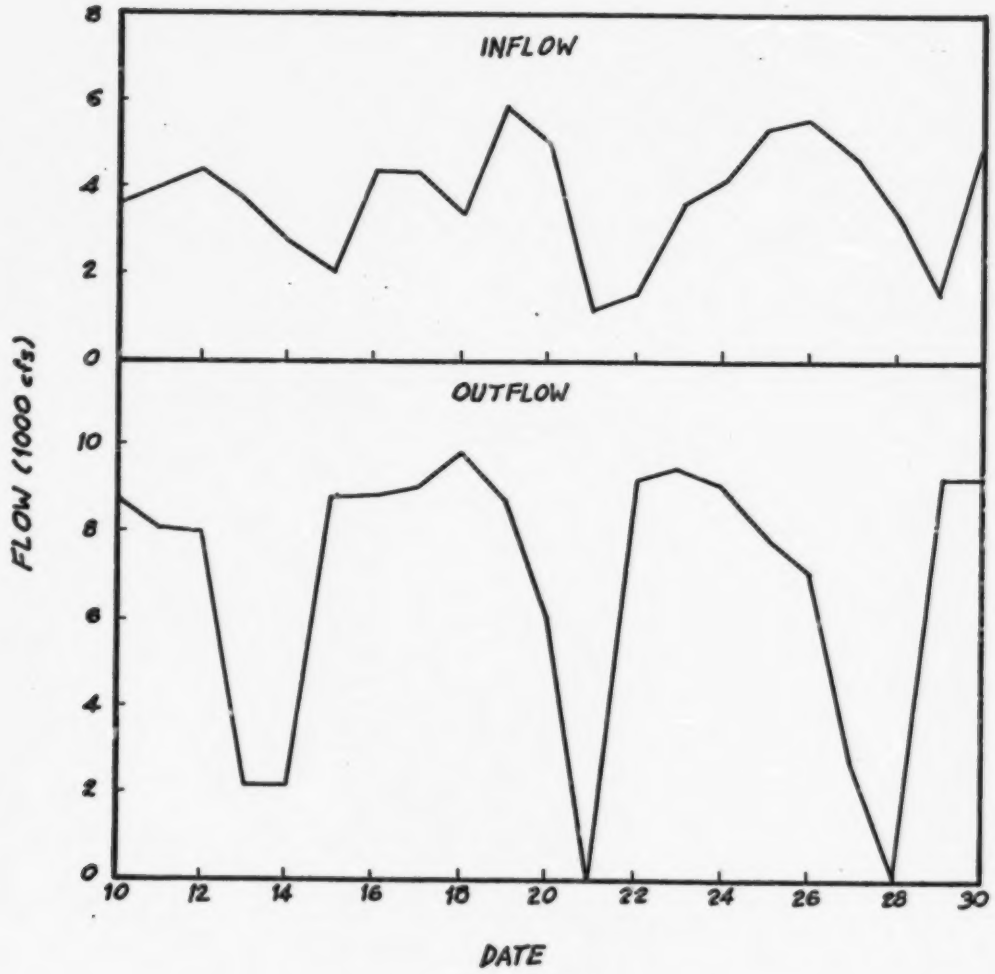


FIGURE 8 - FLOWRATES FOR JULY

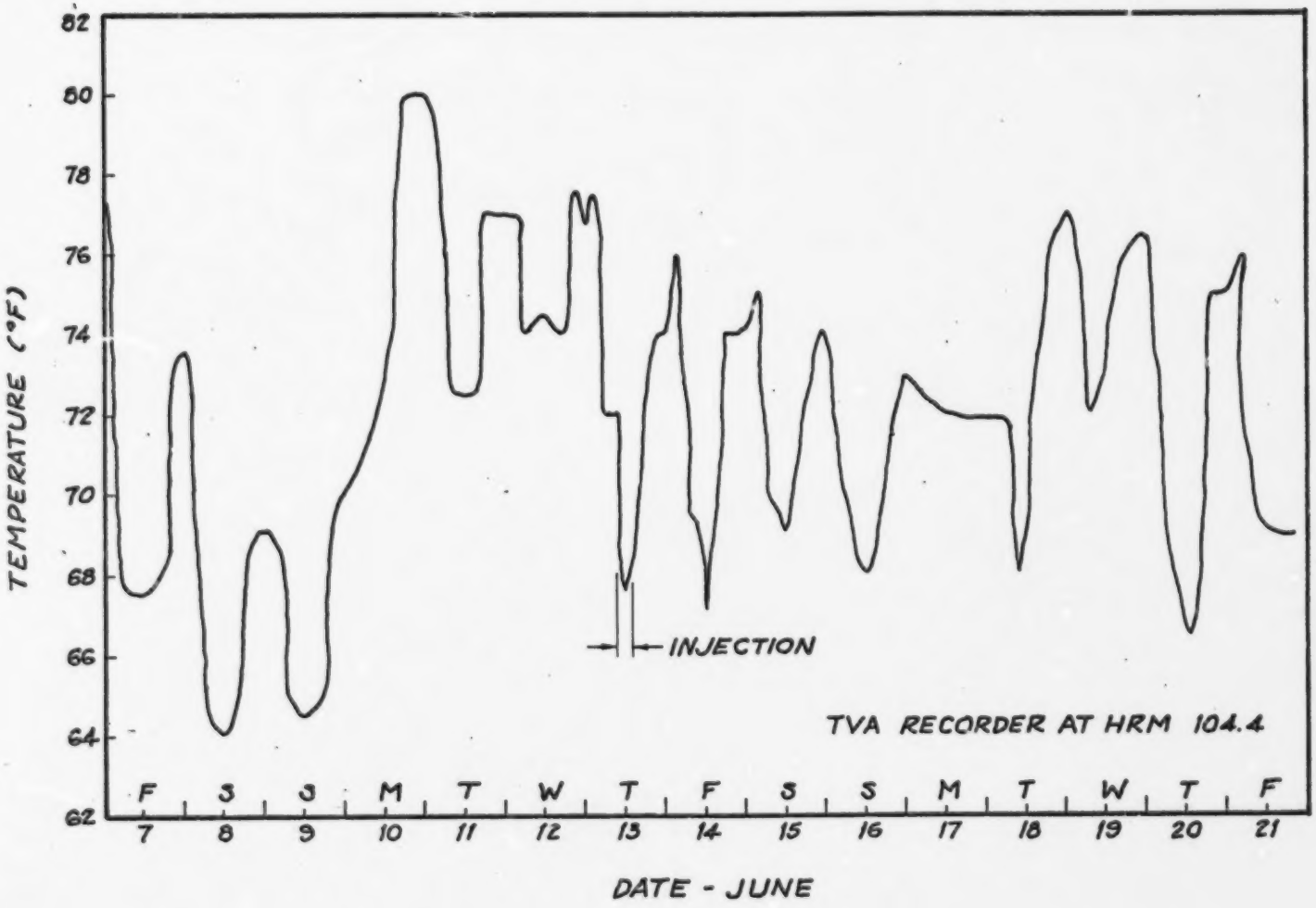


FIGURE 9 - INFLOW TEMPERATURES FOR JUNE

ending at 2:30 PM. The constant injection rate was maintained by monitoring a scale upon which the dye barrel rested and by adjusting the flow rate by means of a clamp on the discharge hose. The injection was designed to yield a 50-60 μg/l dye concentration in an expected 5500 cfs flow. However, the flow began to drop at about 2:00 PM and concentrations as high as 100μg/l were present near the end of the injection period. The dye was observed to be well mixed and initially confined to the middle third of the stream. However, it was completely mixed laterally by HRM 102, or about 4 miles upstream of the plunge point. The mixed temperature of the pulse was 20° - 21°C. This was the coldest water to enter the reservoir during the week.

The second dye injection was intended to tag the warm North Fork component of the flow, and was made on July 10, 1968, from 6:00 PM to 12:00 PM. During this period, 108 pounds of pure dye was injected into the spillway as before. This rate was designed to yield about 75 μg/l of dye in the 600 cfs flow from the North Fork or 40 μg/l in the combined flow of about 1100 cfs. The dye appeared to be well mixed as before.

RESULTS

Movement of the Tracer Cloud

During the June series, the dye was injected initially in water with a mixed temperature of 22° to 23°C, except for the tail, which was about 24°C. On June 15th, the dye cloud reached the plunge point, which was readily detected on the surface by the difference in turbidity and the accumulation of logs and other debris and which ran diagonally from HRM 96.0 to HRM 97.5. When the dye cloud passed the plunge point it plunged to a depth where the water density was equal to its own, except for a small amount of dye that remained on the surface. This surface dye was probably that which was initially held along the banks in "dead zones" upriver, warmed by the sun, and floated downstream on the surface later. The dye cloud then continued to flow through the reservoir as an interflow, with its center at the 22.5°C level. The interflow was confined to a 15-foot layer centered 20 to 25 feet below the surface. The forward velocity was approximately 0.5 mi/day.

There appeared to be very little vertical diffusion downward from the dye cloud and only slight diffusion upward. There were no problems involved with following and measuring the dye concentrations except at concentrations of less than 0.5 μg/l, as previously explained.

However, on June 25th, a storm with winds averaging about 30 mph began, and, by June 27th, it had completely destratified the first 20 feet of the reservoir and mixed the next 20 feet sufficiently so that the dye concentration was too low to be measured. Also, the storm made maneuvering the boat so difficult that only a few stations could be sampled

during this three-day period. Concentration and temperature profiles for the June experiment are shown in Figures 10 through 20.

The second, or July, injection was made on July 10, 1968, and the initial water temperature for most of the dye was about 24.6°C. The dye cloud passed through the reservoir in a manner similar to the first dye cloud, in 20 to 30-feet thick interflow, centered about 30 feet below the surface. The dye cloud could not be measured after July 18, 1968, due to the low concentrations. Concentration and temperature profiles for the July experiment are shown in Figures 21 through 28.

Once the tracer cloud passed the plunge point, the peak dye concentrations in the July test declined more rapidly than in the June test, and the flow became a true interflow about HRM 93 on the fourth or fifth day of the tests. However, before this happened, the concentrations were quite similar. The rapid decrease in concentration in July was due to the greater thickness of the interflow, which was almost twice as thick as in June, which allowed a greater dilution. This, in turn, was caused by the shape of the stability profile, as will be shown later.

Mixing in the Reservoir

Lateral Mixing

Both dye injections were well mixed laterally in the main reservoir. However, it was found that virtually no dye mixed or flowed into the embayments after June 20th, which roughly corresponded to the initiation of a continual, slow drawdown of the reservoir for the remainder of the summer. The rate of drawdown was approximately 0.25 feet per day. An illustration of this typical occurrence is presented in Figure 29. The

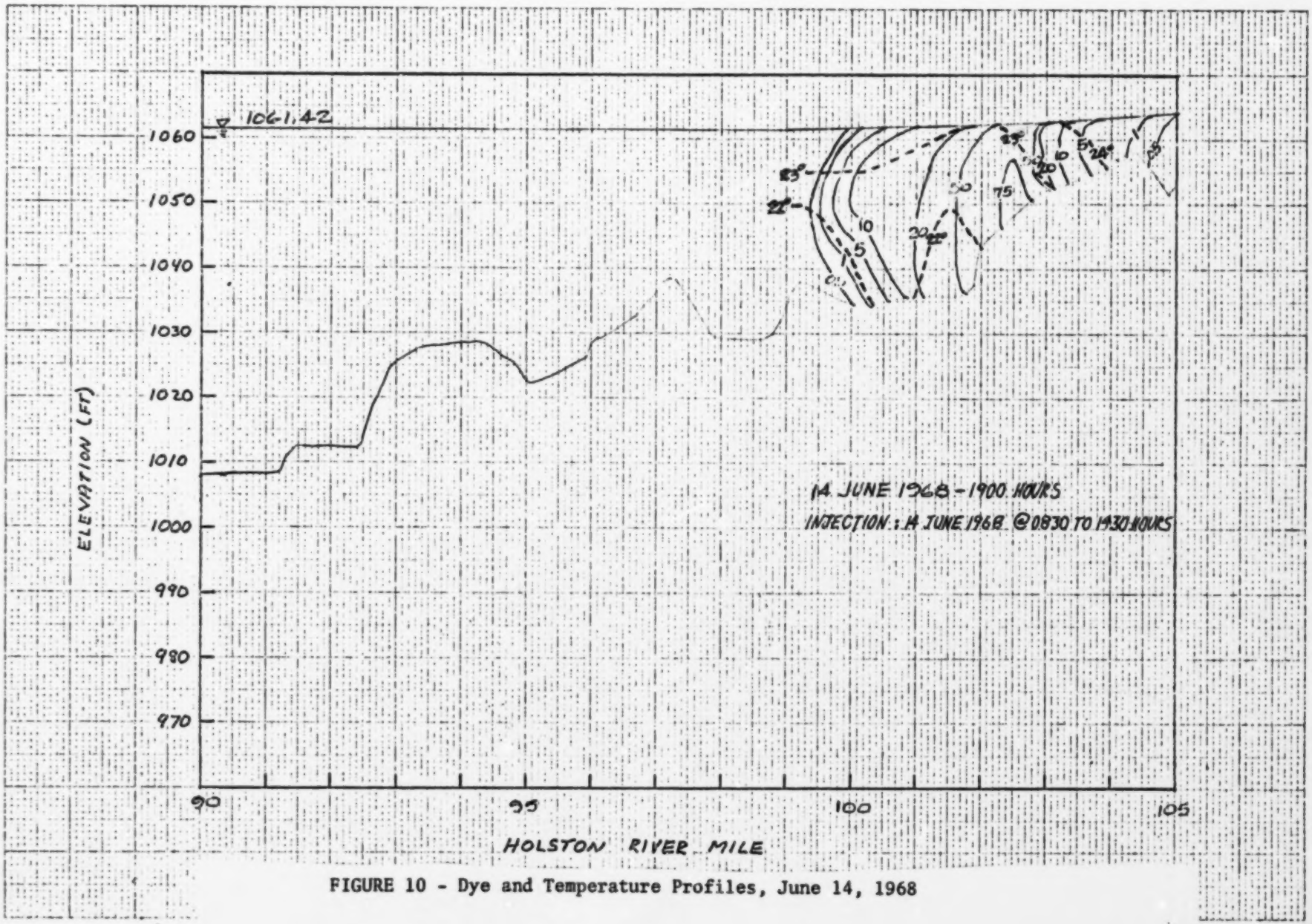


FIGURE 10 - Dye and Temperature Profiles, June 14, 1968

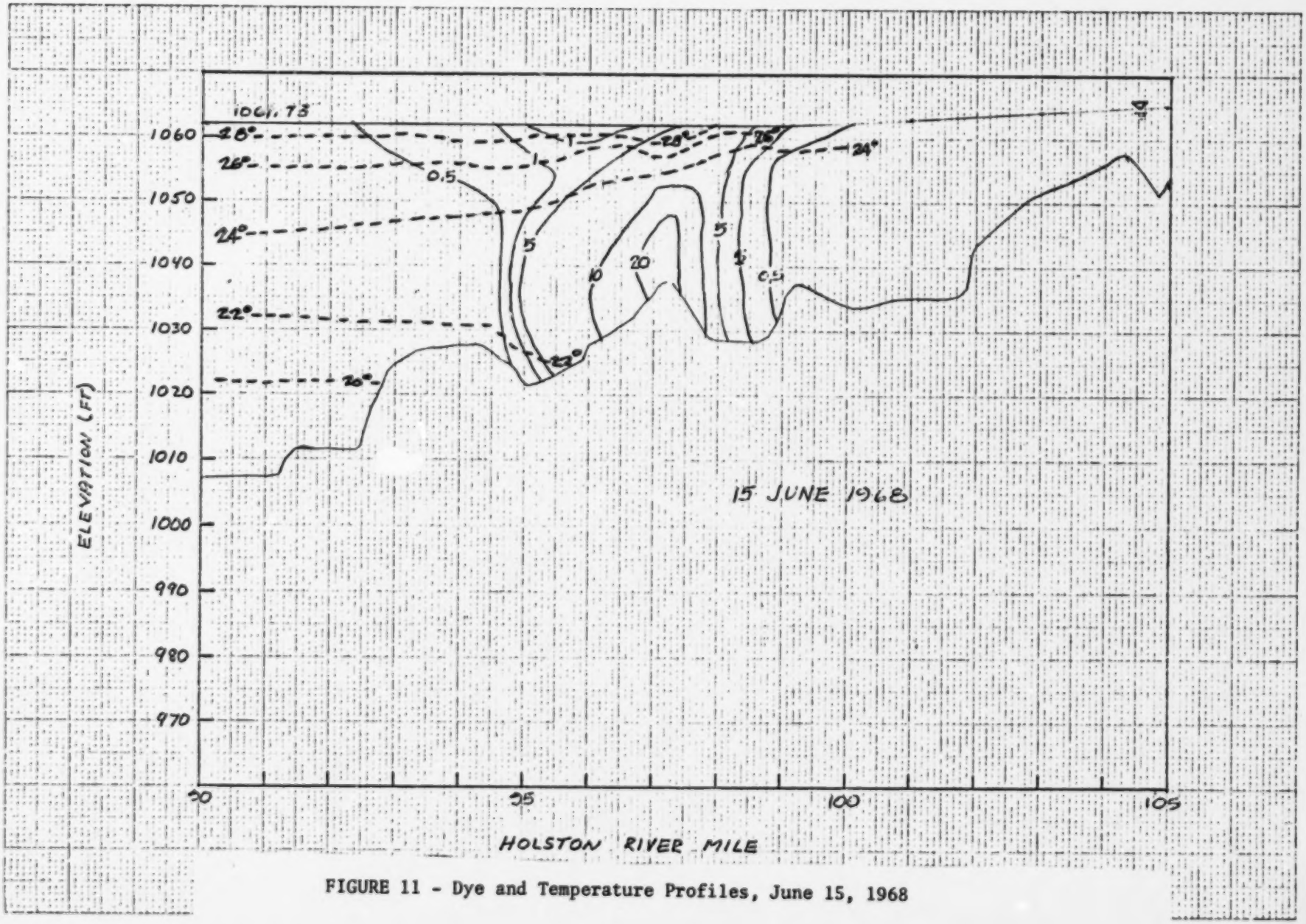


FIGURE 11 - Dye and Temperature Profiles, June 15, 1968

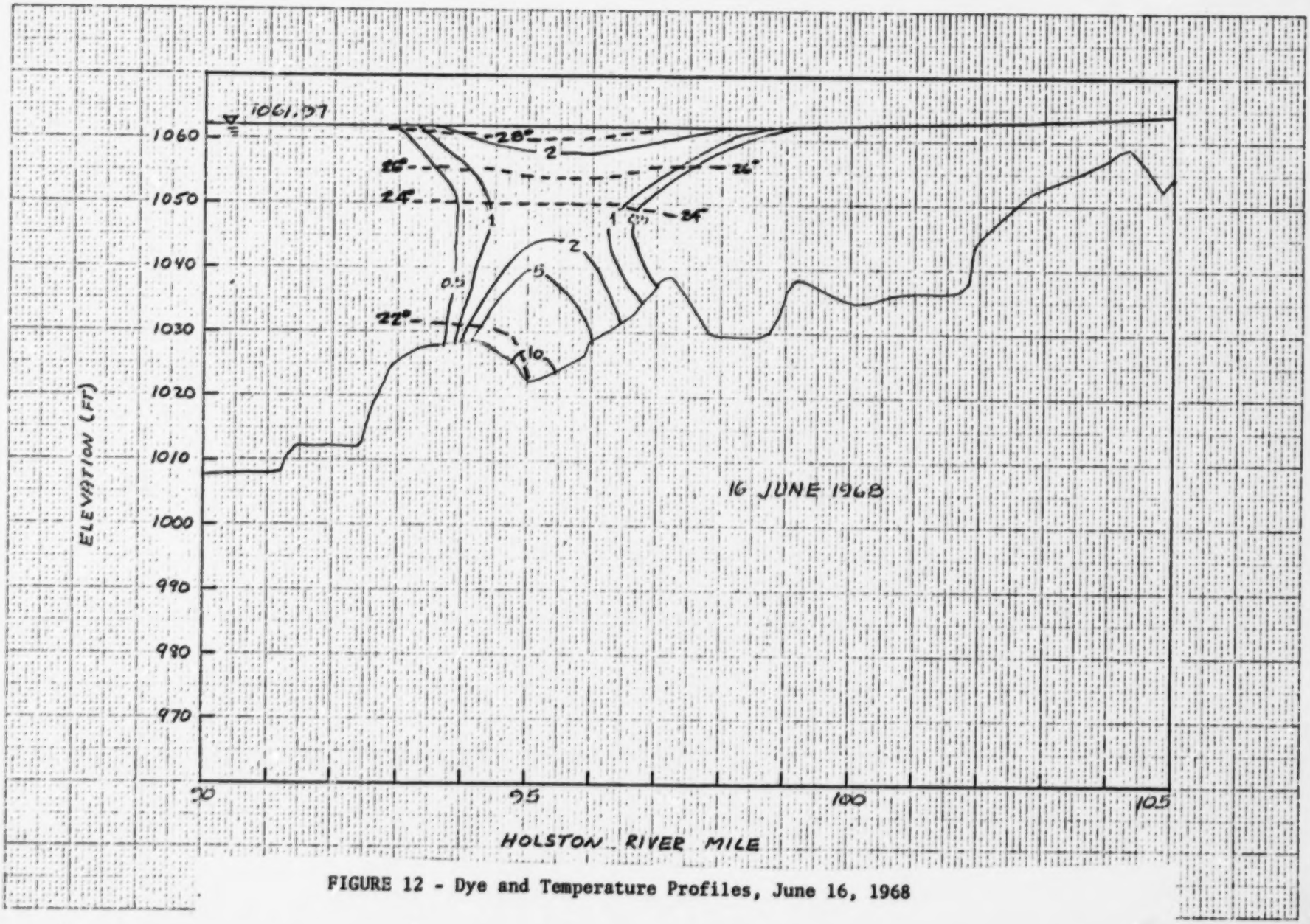


FIGURE 12 - Dye and Temperature Profiles, June 16, 1968

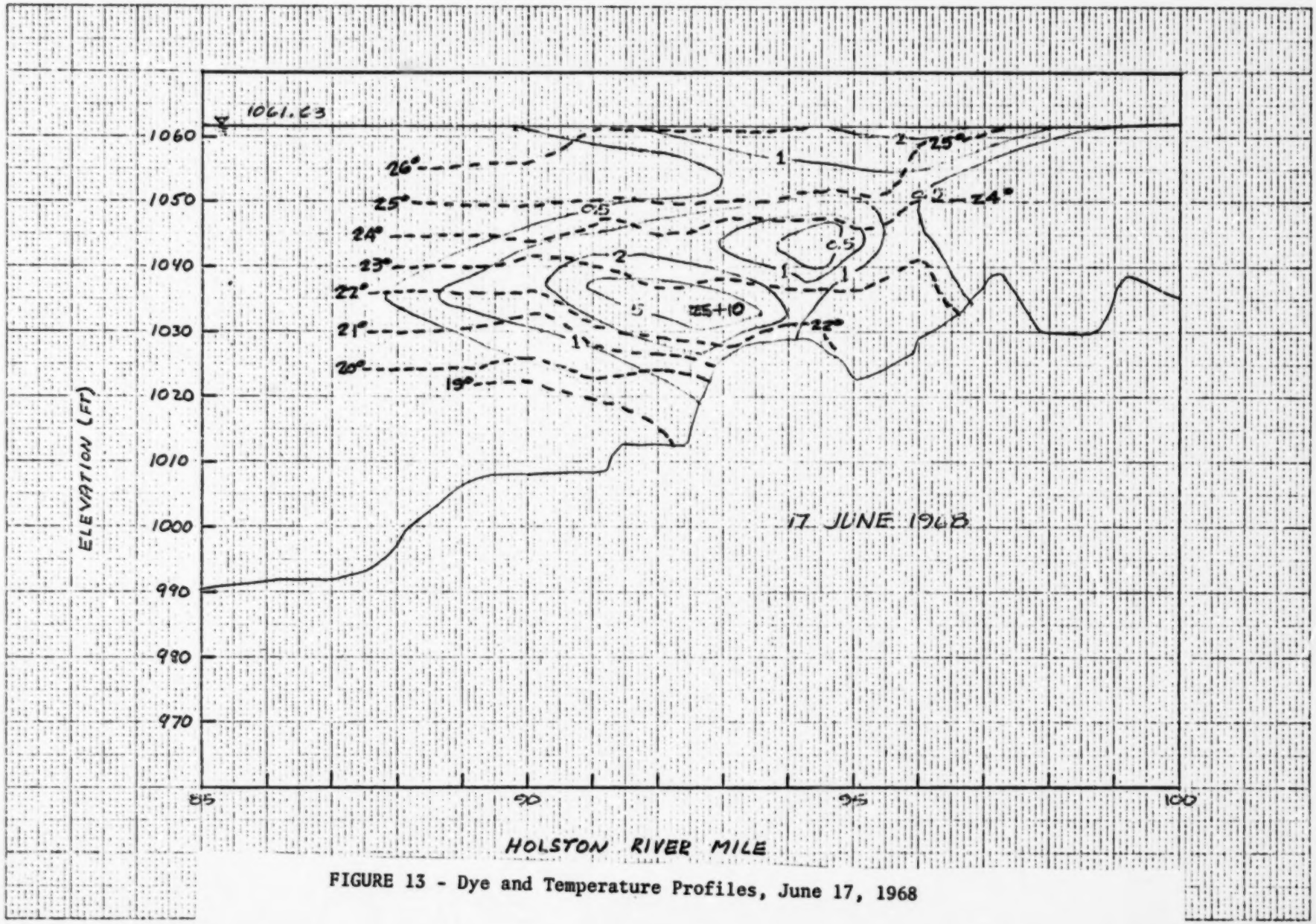


FIGURE 13 - Dye and Temperature Profiles, June 17, 1968

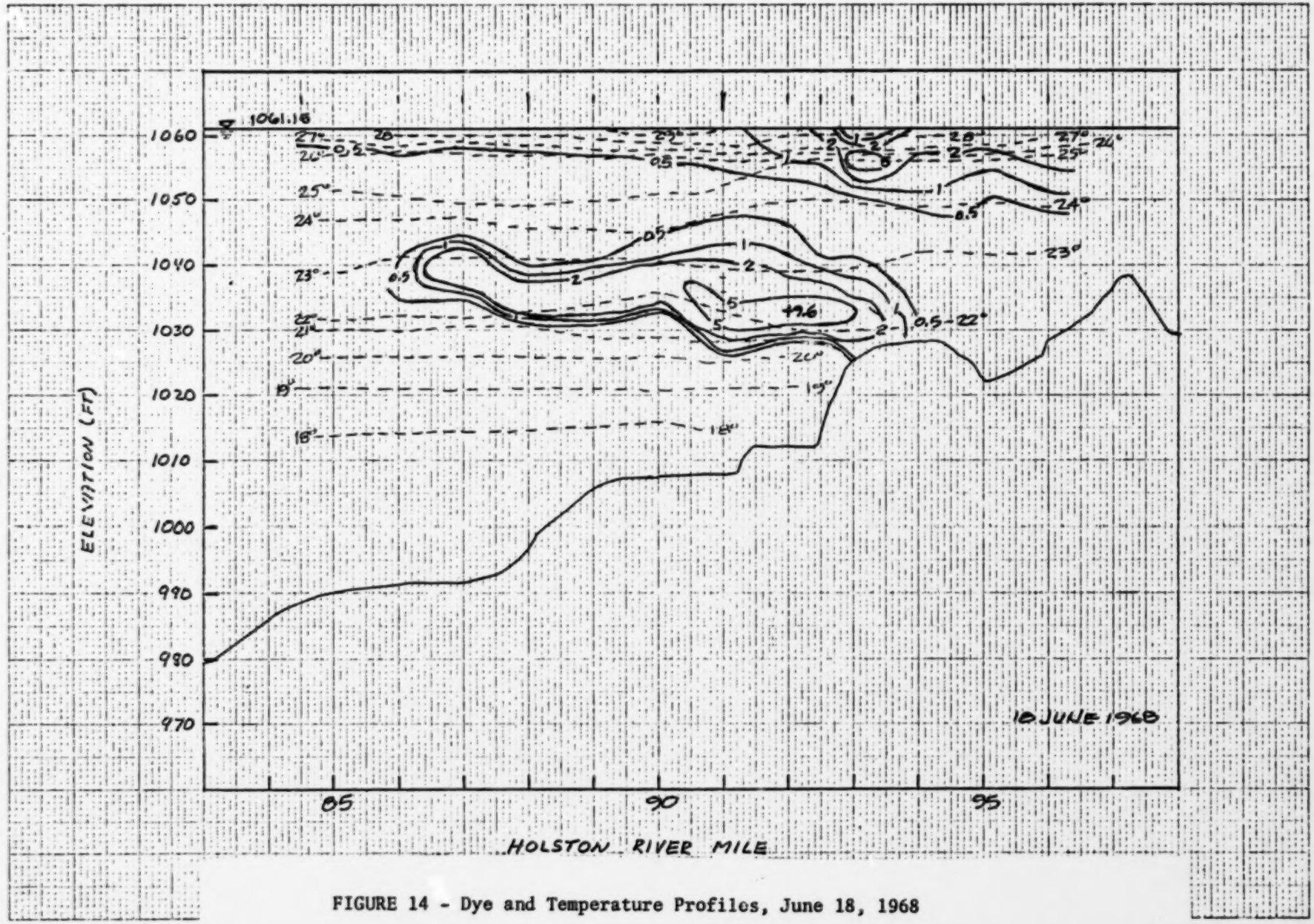


FIGURE 14 - Dye and Temperature Profiles, June 18, 1968

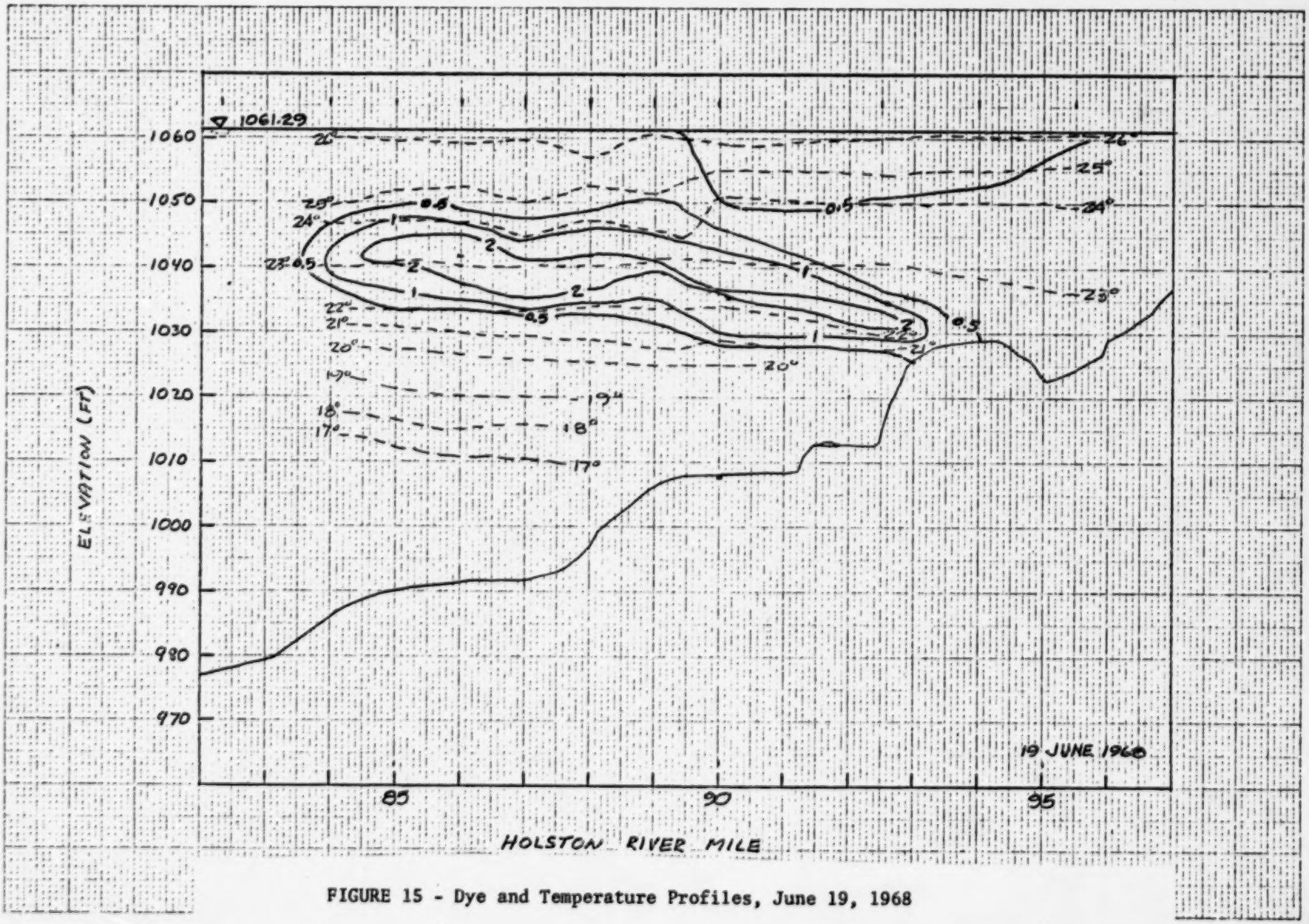


FIGURE 15 - Dye and Temperature Profiles, June 19, 1968

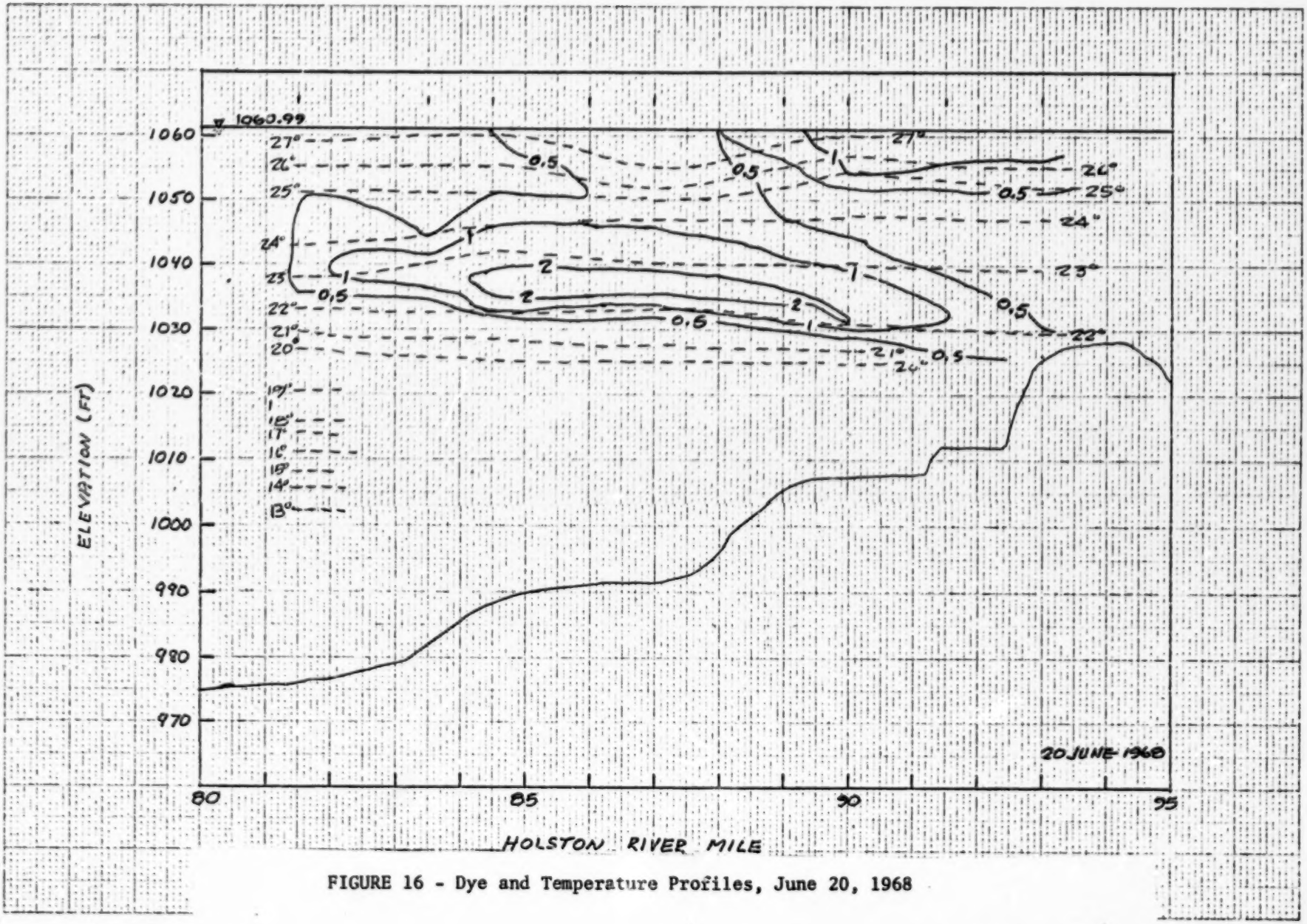


FIGURE 16 - Dye and Temperature Profiles, June 20, 1968

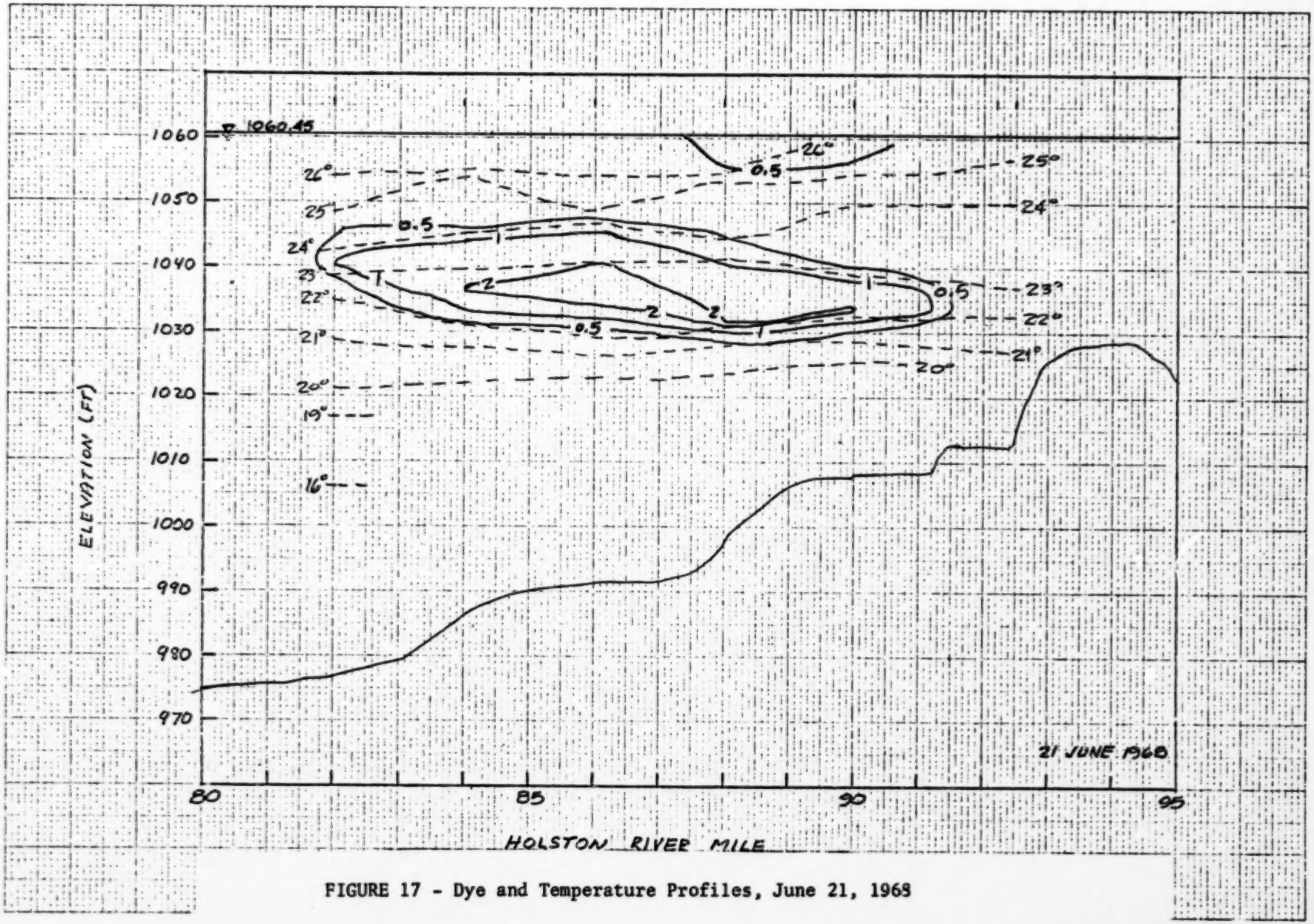


FIGURE 17 - Dye and Temperature Profiles, June 21, 1968

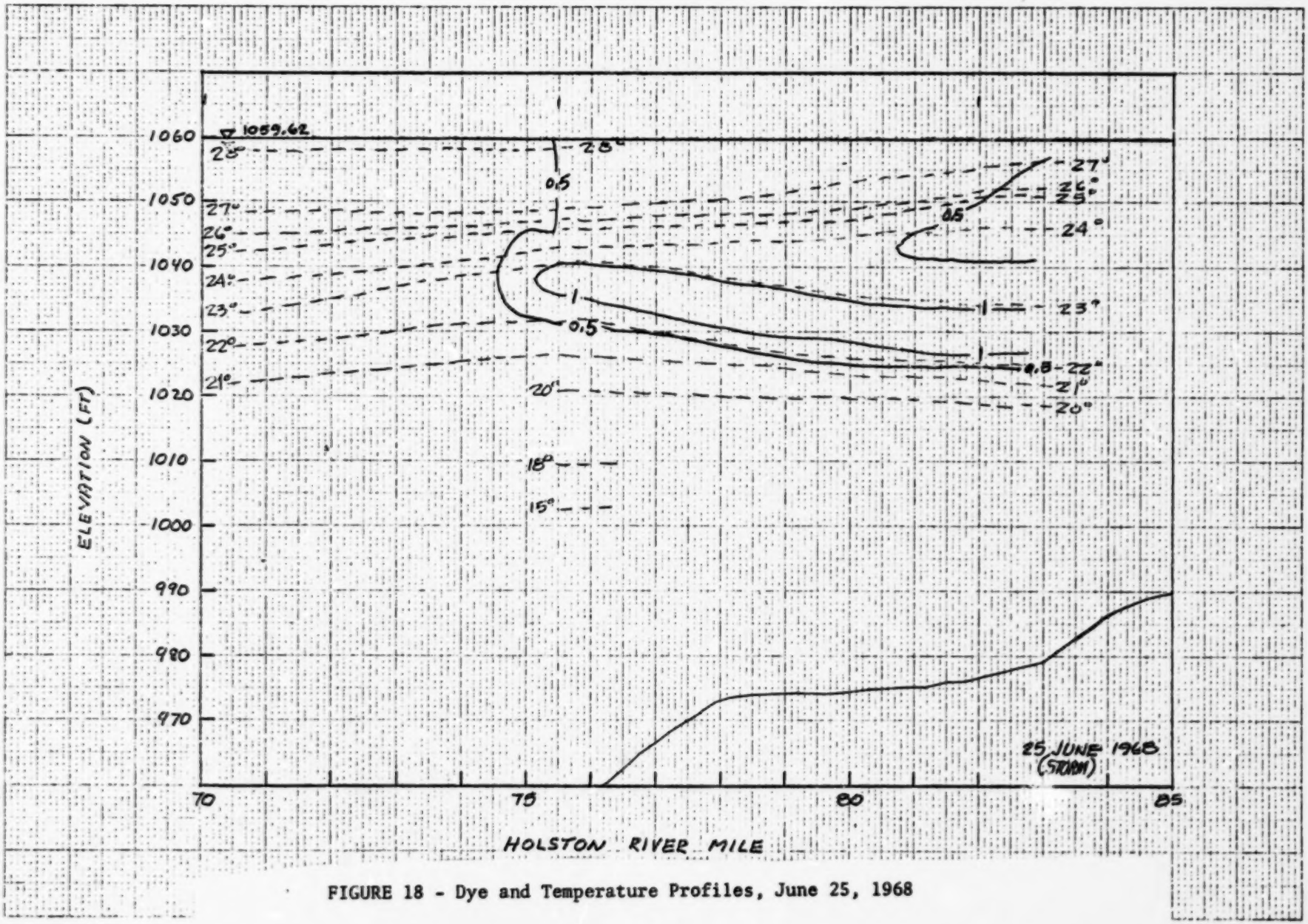


FIGURE 18 - Dye and Temperature Profiles, June 25, 1968

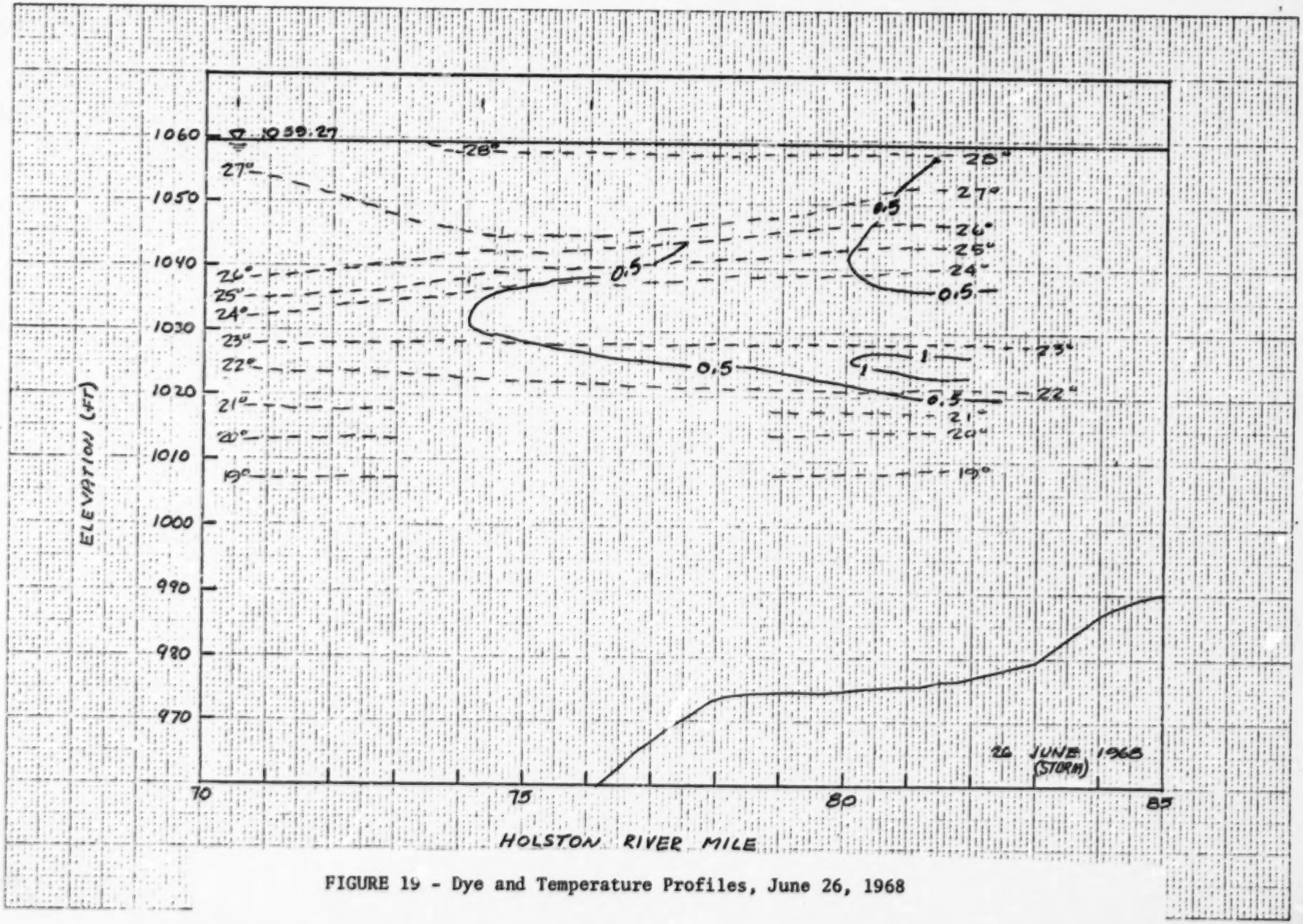


FIGURE 19 - Dye and Temperature Profiles, June 26, 1968

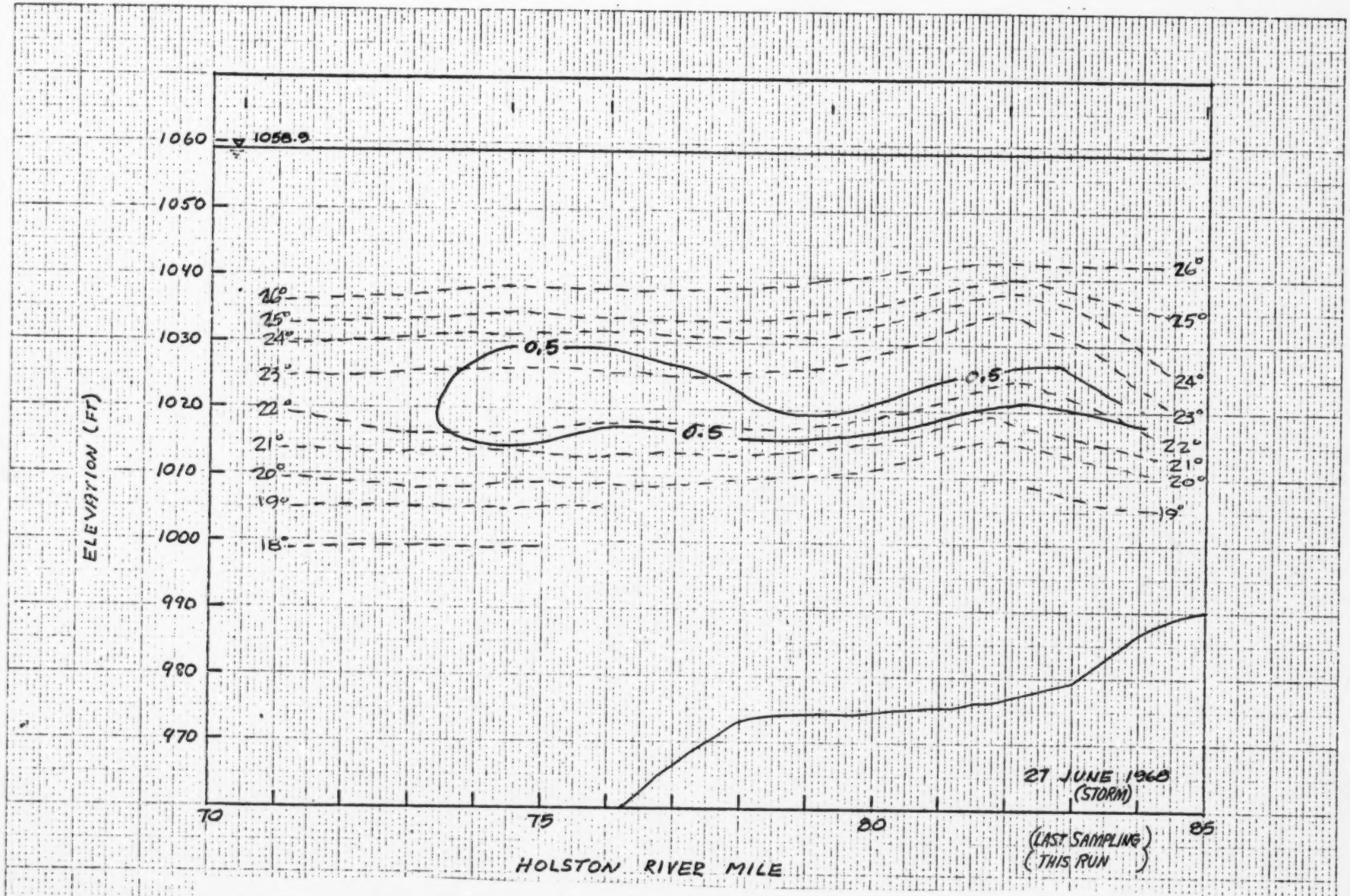


FIGURE 20 - Dye and Temperature Profiles, June 27, 1968

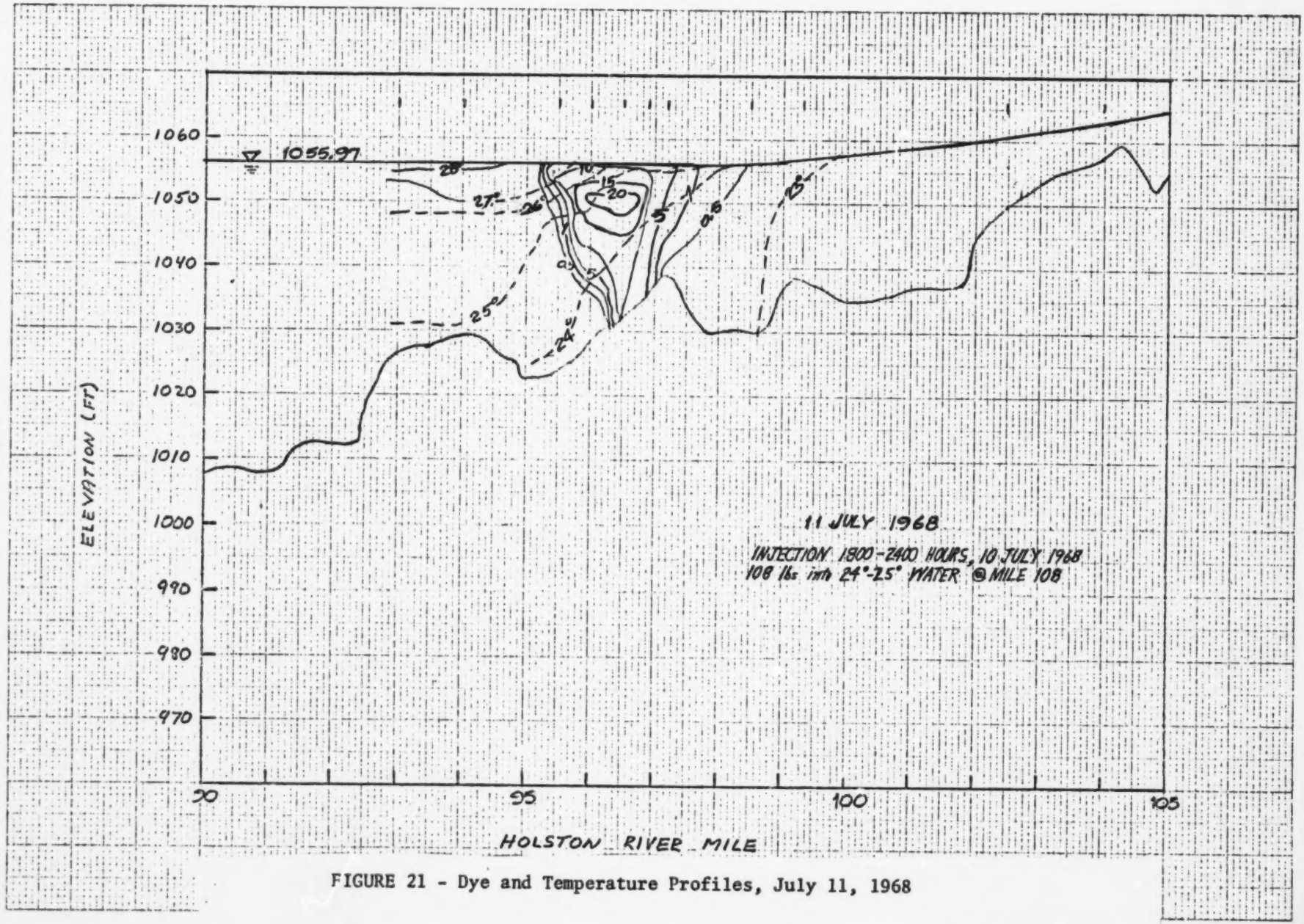


FIGURE 21 - Dye and Temperature Profiles, July 11, 1968

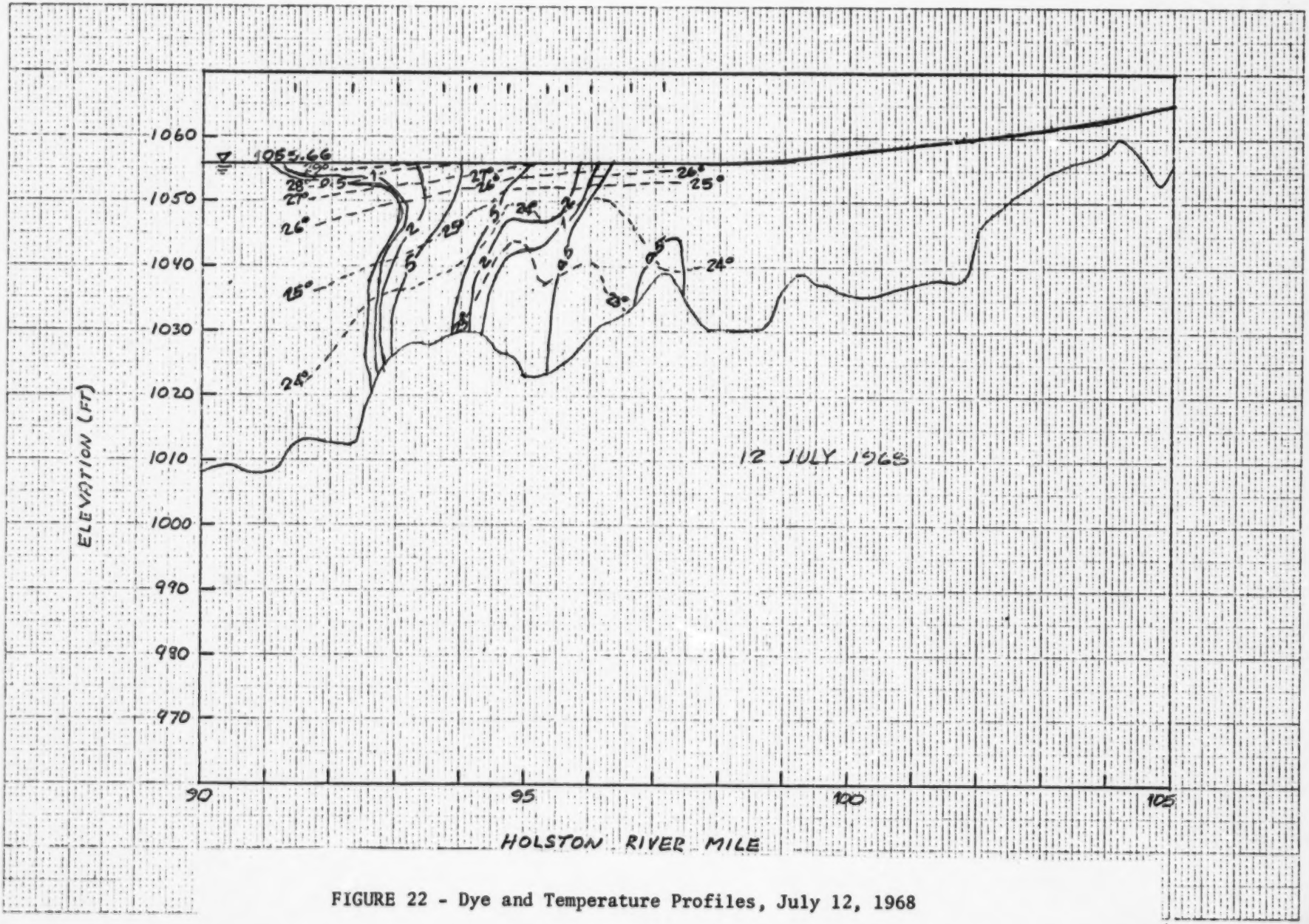


FIGURE 22 - Dye and Temperature Profiles, July 12, 1968

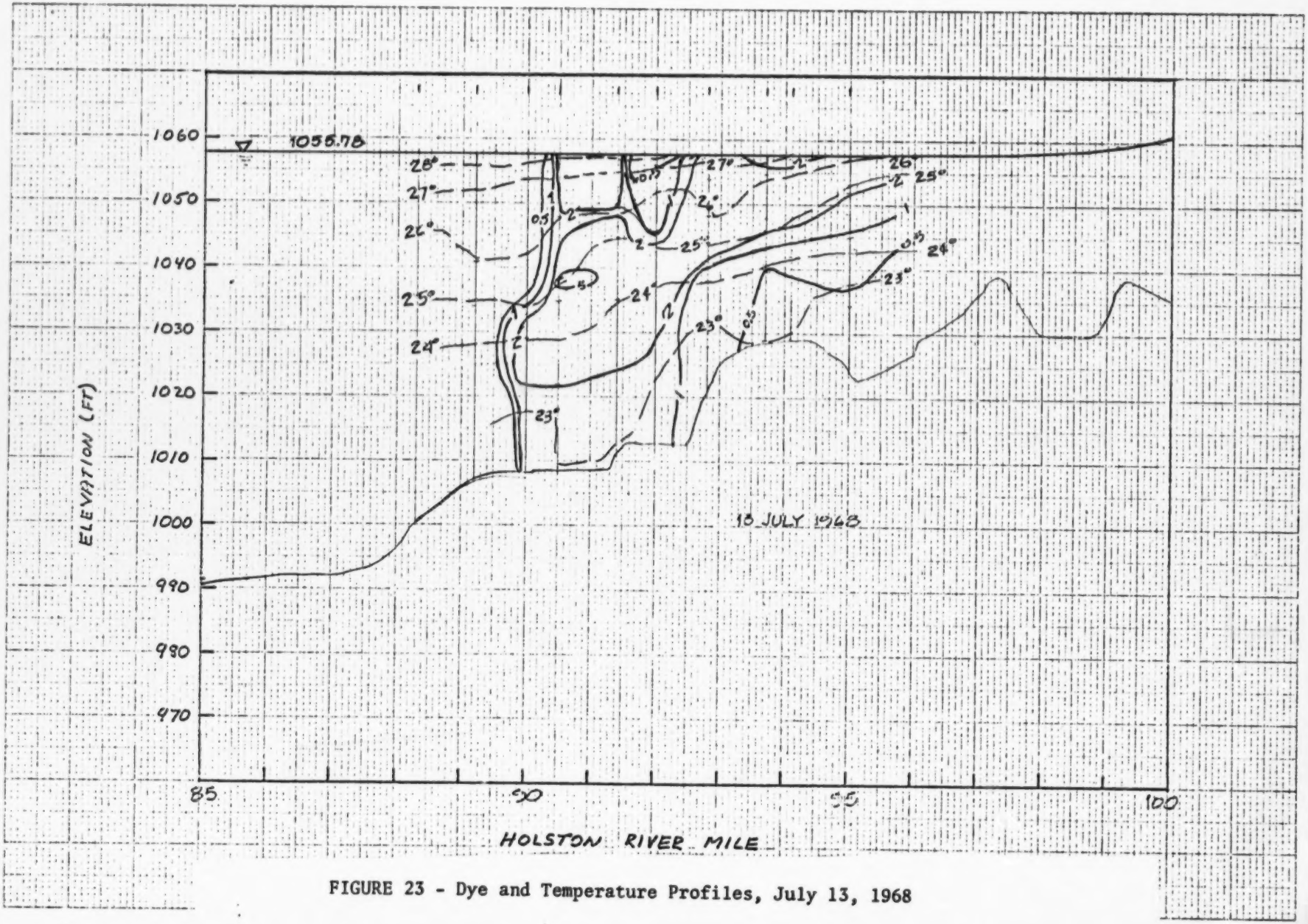


FIGURE 23 - Dye and Temperature Profiles, July 13, 1968

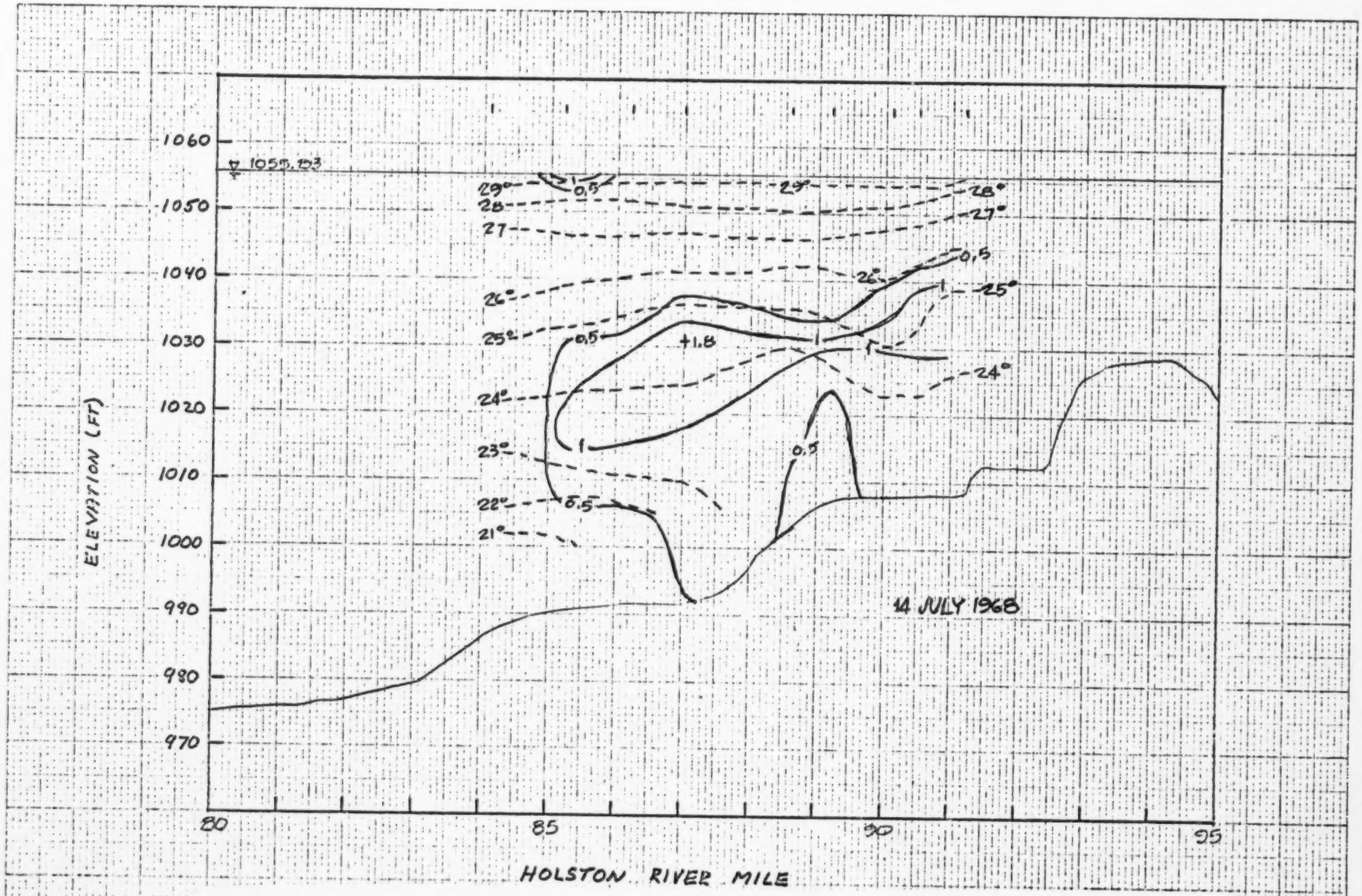


FIGURE 24 - Dye and Temperature Profiles, July 14, 1968

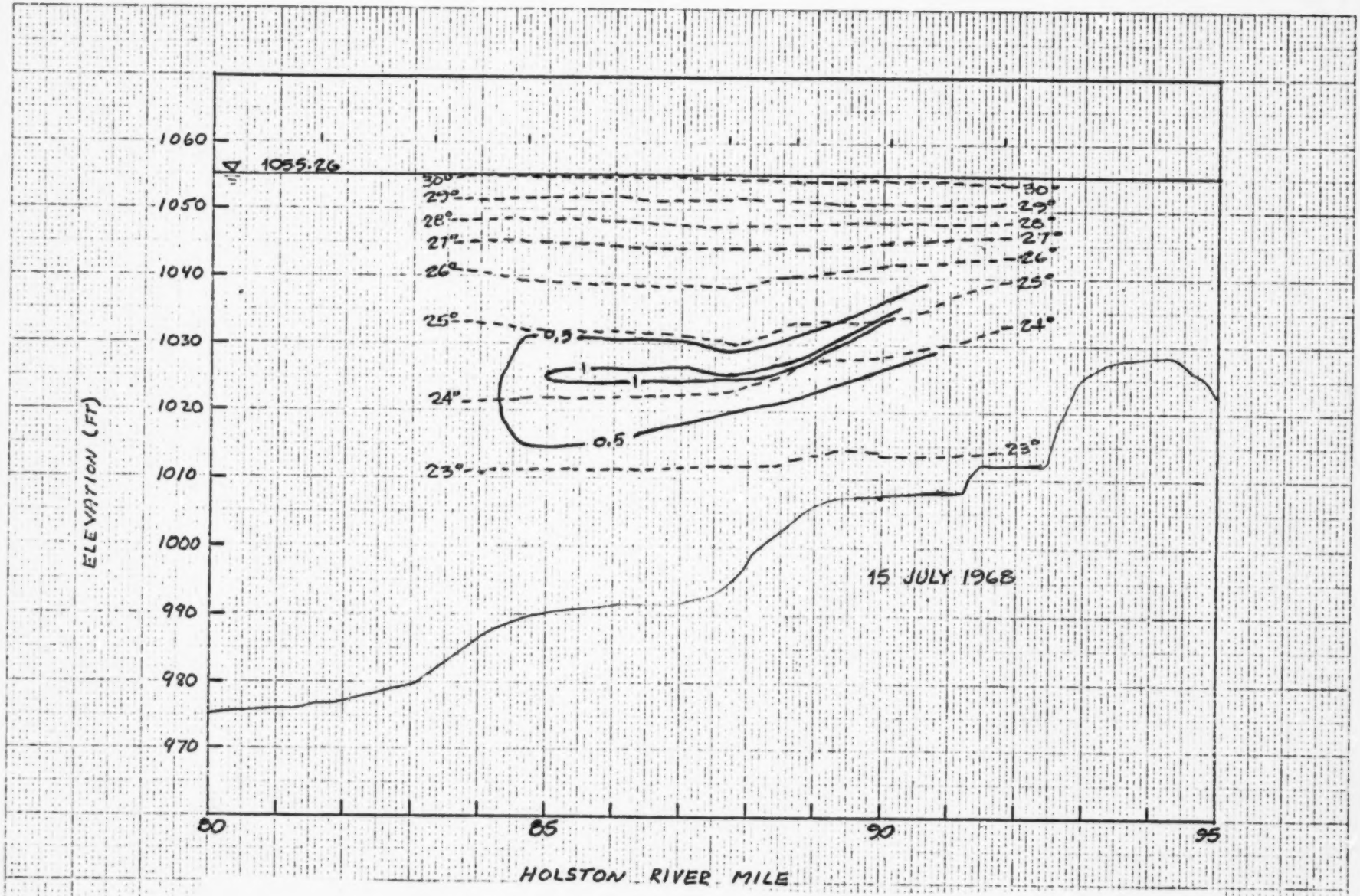


FIGURE 25 - Dye and Temperature Profiles, July 15, 1968

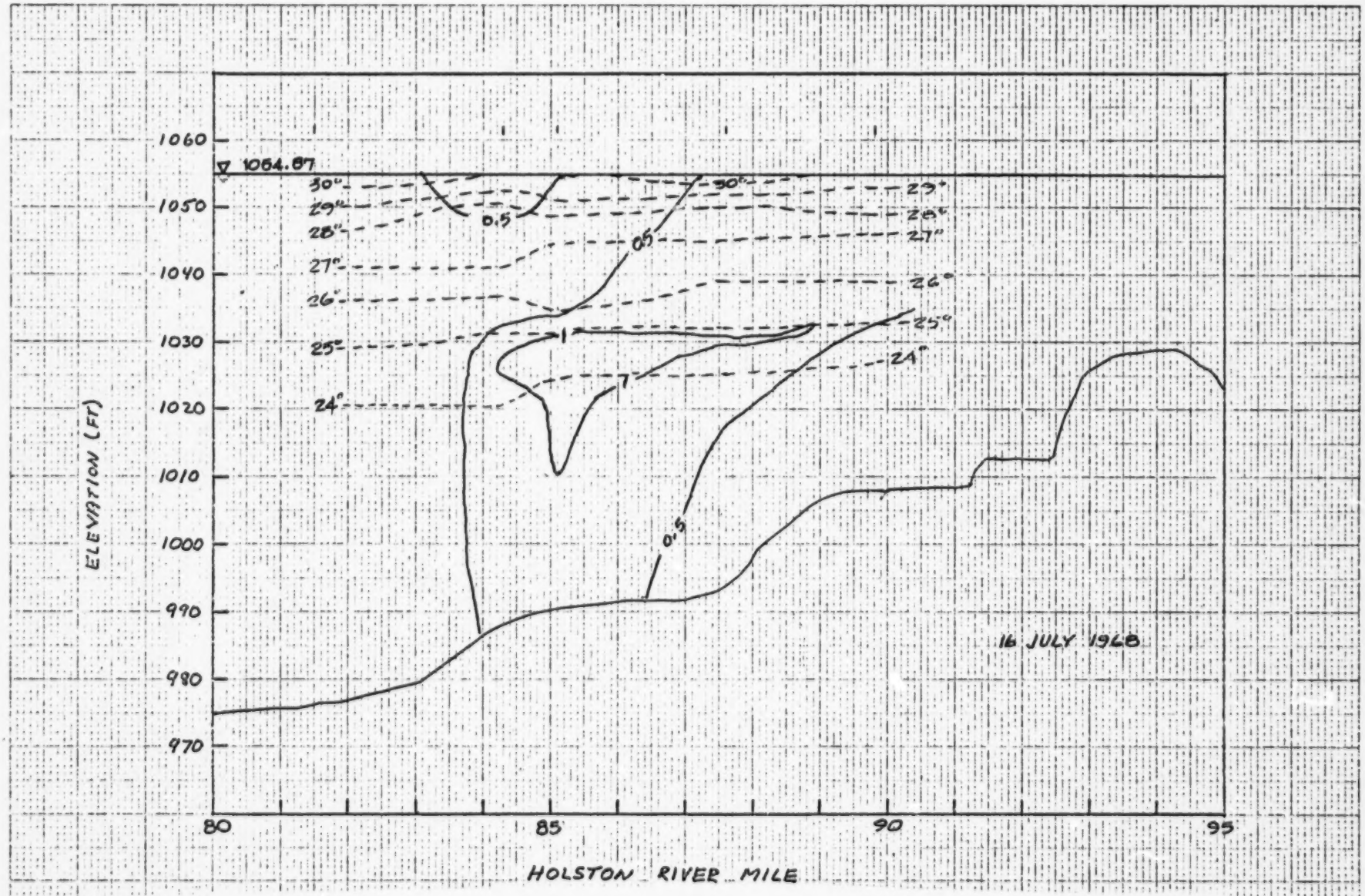


FIGURE 26 - Dye and Temperature Profiles, July 16, 1968

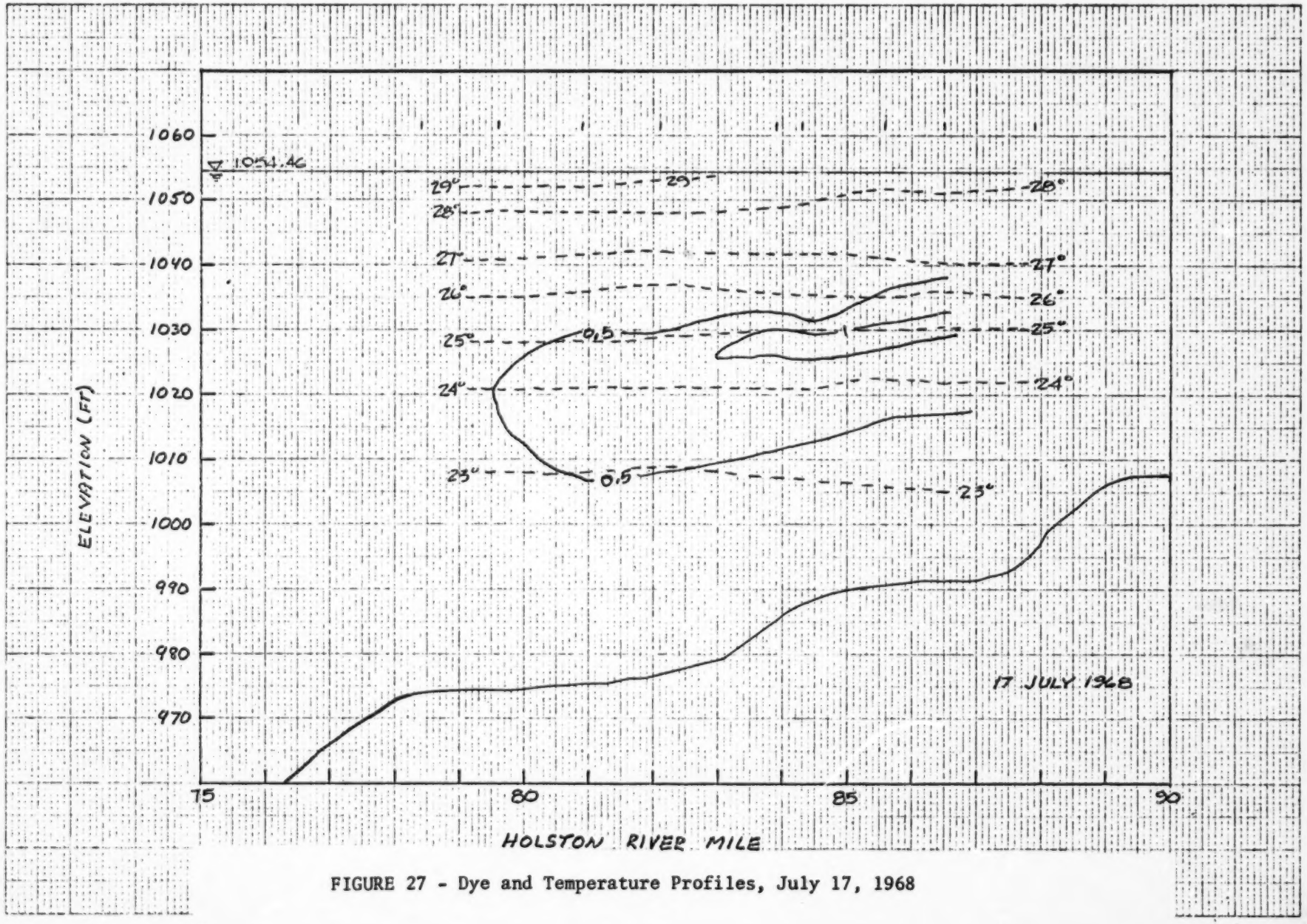


FIGURE 27 - Dye and Temperature Profiles, July 17, 1968

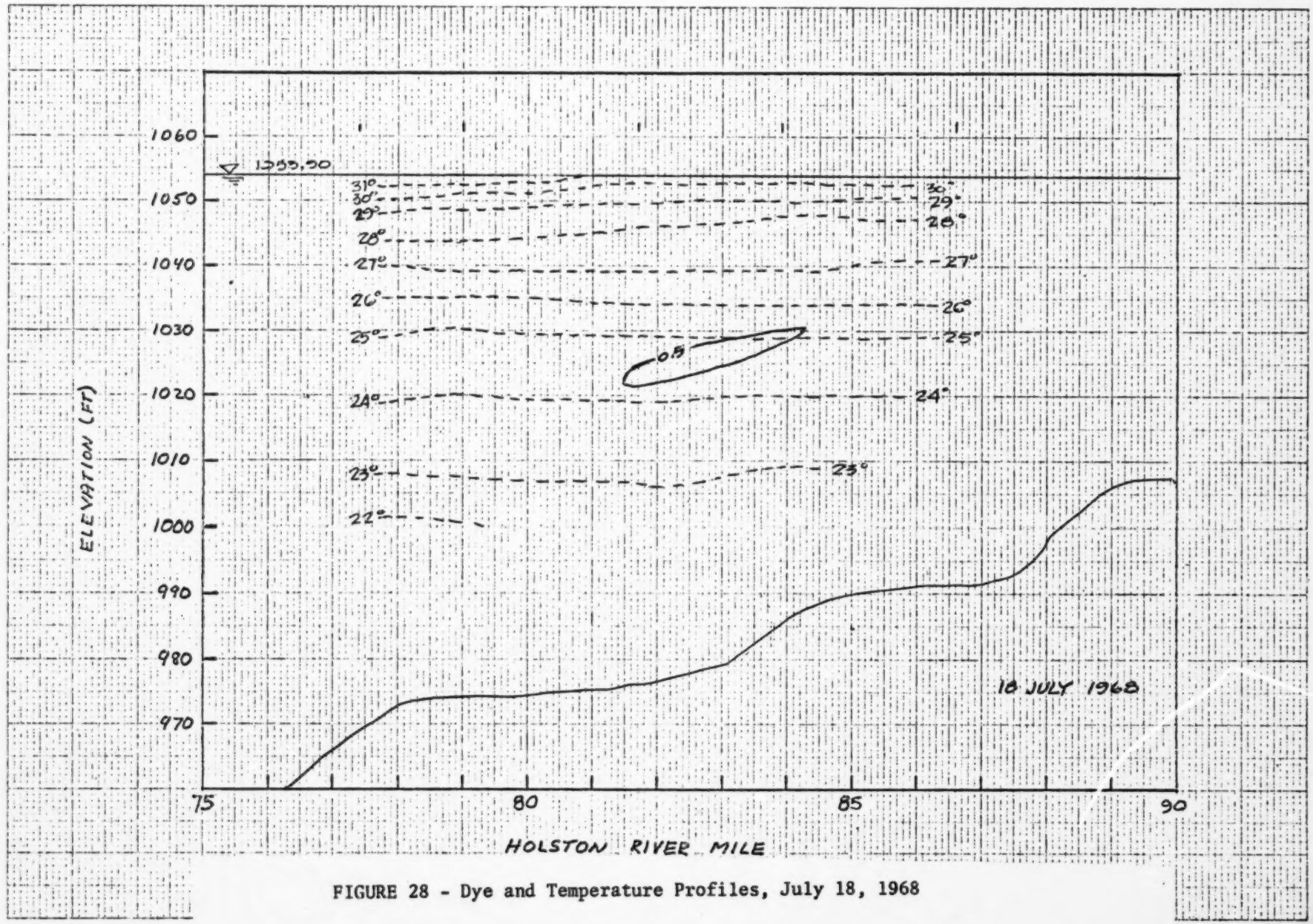
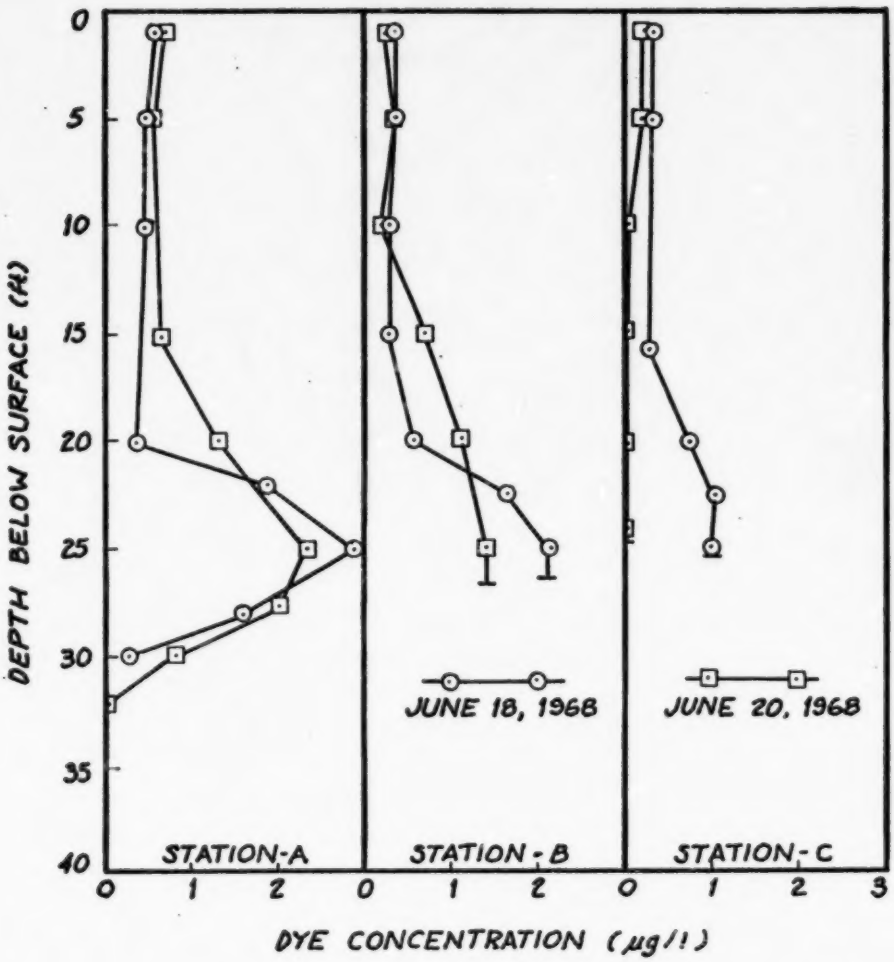


FIGURE 28 - Dye and Temperature Profiles, July 18, 1968



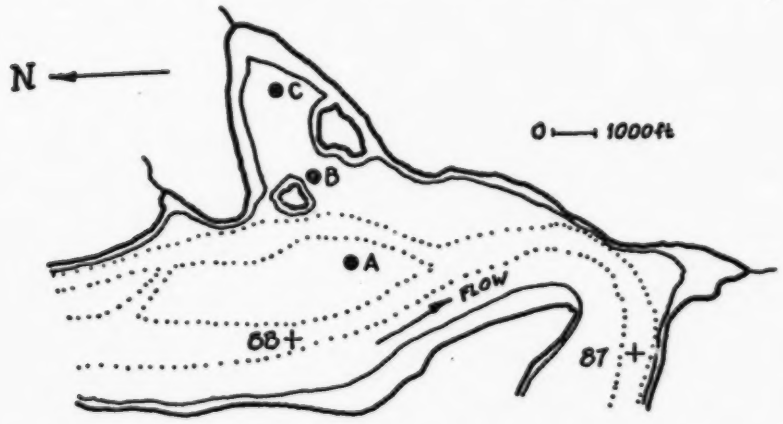


FIGURE 29 - EMBAYMENT DYE PROFILES

embayment at HRM 87.9 is shown with the three sampling locations. Station A was in mid-channel, Station B was about 500 feet into the embayment, and Station C was about 2000 feet into the embayment. The dye concentrations with the corresponding depths at each station show that, after the reservoir drawdown began, no dye was found in the embayments past the first few feet. This was consistently found to be true for the entire tests.

The data demonstrate that it would be virtually impossible for polluted slugs of water to move up into the embayments and affect possible water supplies as long as the reservoir is being drawn down even slightly. However, even very slight fluctuations in surface elevation will allow enough movement of water into the embayments to carry possibly polluted water passing by in the main channel into the embayments. Between June 16 and June 20, the surface elevation fluctuated about 0.2 to 0.4 feet per day. This allowed dye to move as far as 2000 feet into the embayments.

During the period the reservoir is filling in the spring, there is no way to keep possible polluted inflow from flowing into the embayments. However, year-round water intakes will be below winter low water level, and should not be affected by incoming polluted water in the spring, which would be on or near the surface.

Possible polluted slugs passing through the reservoir in the summer could be kept out of the embayments, where they might affect recreational use or temporary summer water supplies, by applying a slow continuous drawdown to the reservoir during the period the polluted slug is passing through. Danger to permanent water supplies should be

confined to the fall, when cold water moves through the still-warm reservoir as an underflow.

Vertical Mixing

The vertical eddy diffusivity, D_z, can be defined as

$$D_z = \frac{\partial c}{\partial t} \Big/ \frac{\partial^2 c}{\partial z^2} \qquad (9)$$

The apparent vertical eddy diffusivity was computed from the dye cloud results for June 18th and 19th by using the definition above and plotted in Figure 30. For the stratum in which the dye cloud was located, the average value of D_z was found to be about 8 ft^2/day or 0.086 cm^2/sec, and there was a sharp decrease in D_z directly above and below the dye cloud. This value is much lower than those reported by Orlob (18), but it agrees favorably with those reported by Hutchinson (10) for lakes with total depths similar to Cherokee. Orlob's values of D_z were computed from temperature profiles, and it should be noted that these can be affected by solar radiation and back radiation of heat as well as by vertical turbulence.

Stability of Stratification

Since the stability criteria proposed by Taylor (22) and Munk and Anderson (17) both rely on the horizontal velocity gradient with depth (which was not determined since TVA could not participate in the studies as was originally planned) these stability relationships could not be used directly. However, they are basically relationships between the stability parameter, E, where

$$E = \frac{1}{\rho} \frac{\partial \rho}{\partial z} \qquad (10)$$

and the inverse of the vertical diffusivity, and, therefore, the values

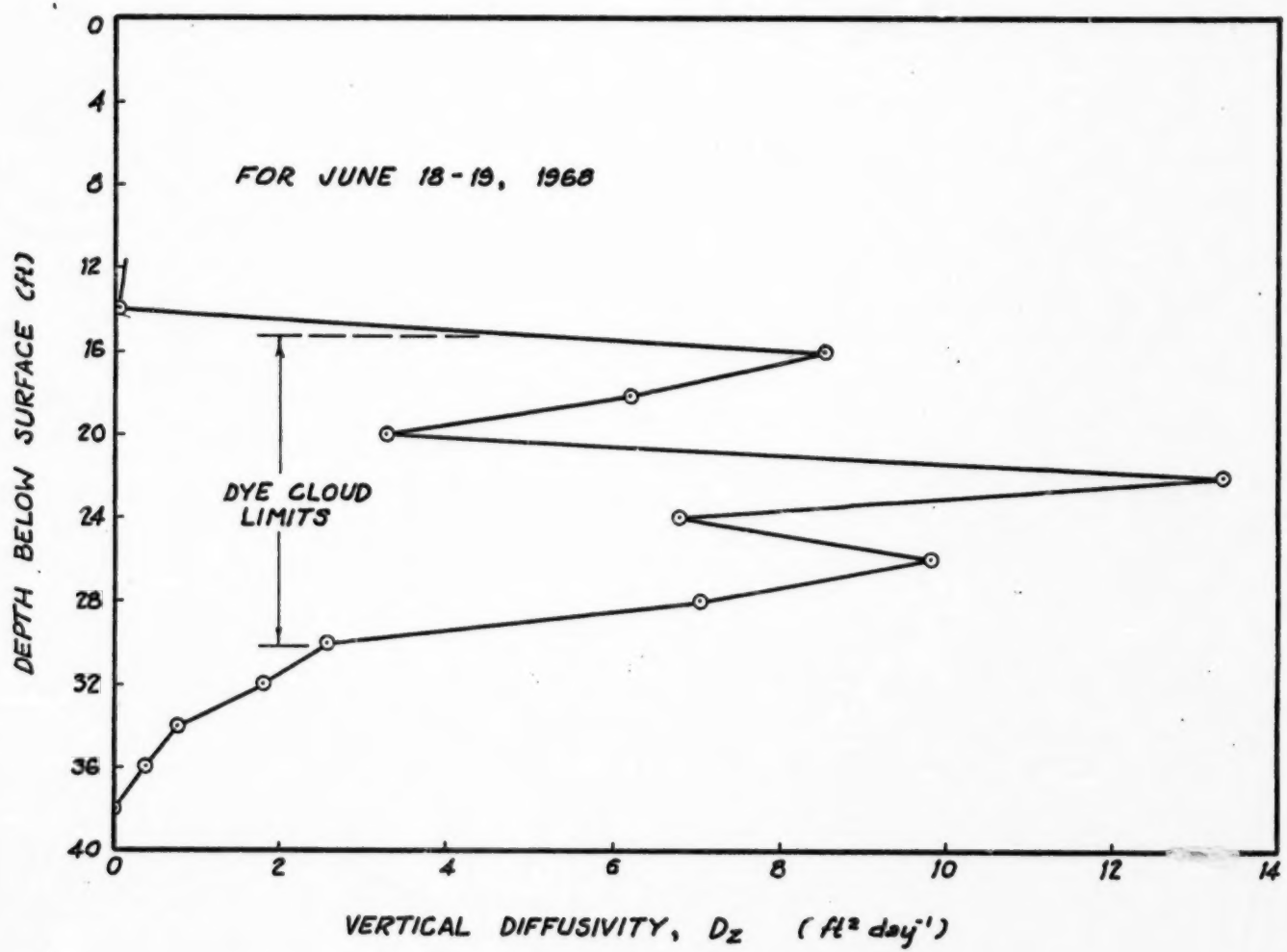


FIGURE 30 - VERTICAL DIFFUSIVITY PROFILE

of E are presented in Figure 31. The stability for the June series is shown to increase considerably below the dye cloud, and this corresponds to a sharp decrease in the calculated value of D_z directly below the cloud. Again, in the July series there was an increase in stability below the dye cloud. The high stability near the surface is a result of solar radiation during the day and is not present after dark, as back radiation cools the surface. Thus, the upper layer is kept mixed by diurnal heating and cooling by the force of the wind.

Keulegan's (15) stability parameter, θ, was estimated to be 0.22 for the June series. Since this is greater than the maximum θ for mixing, there should be no transport of dye in the downward direction. This result is consistent with the observed tracer data, which showed no transport downward from the dye cloud.

There was a weak secondary thermocline directly below the dye cloud at about the 32-foot depth and a primary thermocline about 50 feet below the surface. By the time of the July series, the secondary thermocline had dropped to about 60 feet below the surface and gained in stability. The drop in the dpeth of the thermocline is due to the fact that all withdrawals through the dam are made below the level of the thermocline, while all inflow enters the reservoir above it.

Longitudinal Dispersion

The longitudinal dispersion coefficient, D_L, and the average residence time, t_{ave}, were determined at several stations for the June dye injection by fitting the observed time-concentration data to the reduced form of the solution to the conservation equation (equation 7) as previously described. The fitted time-concentration curves and the observed concentrations at

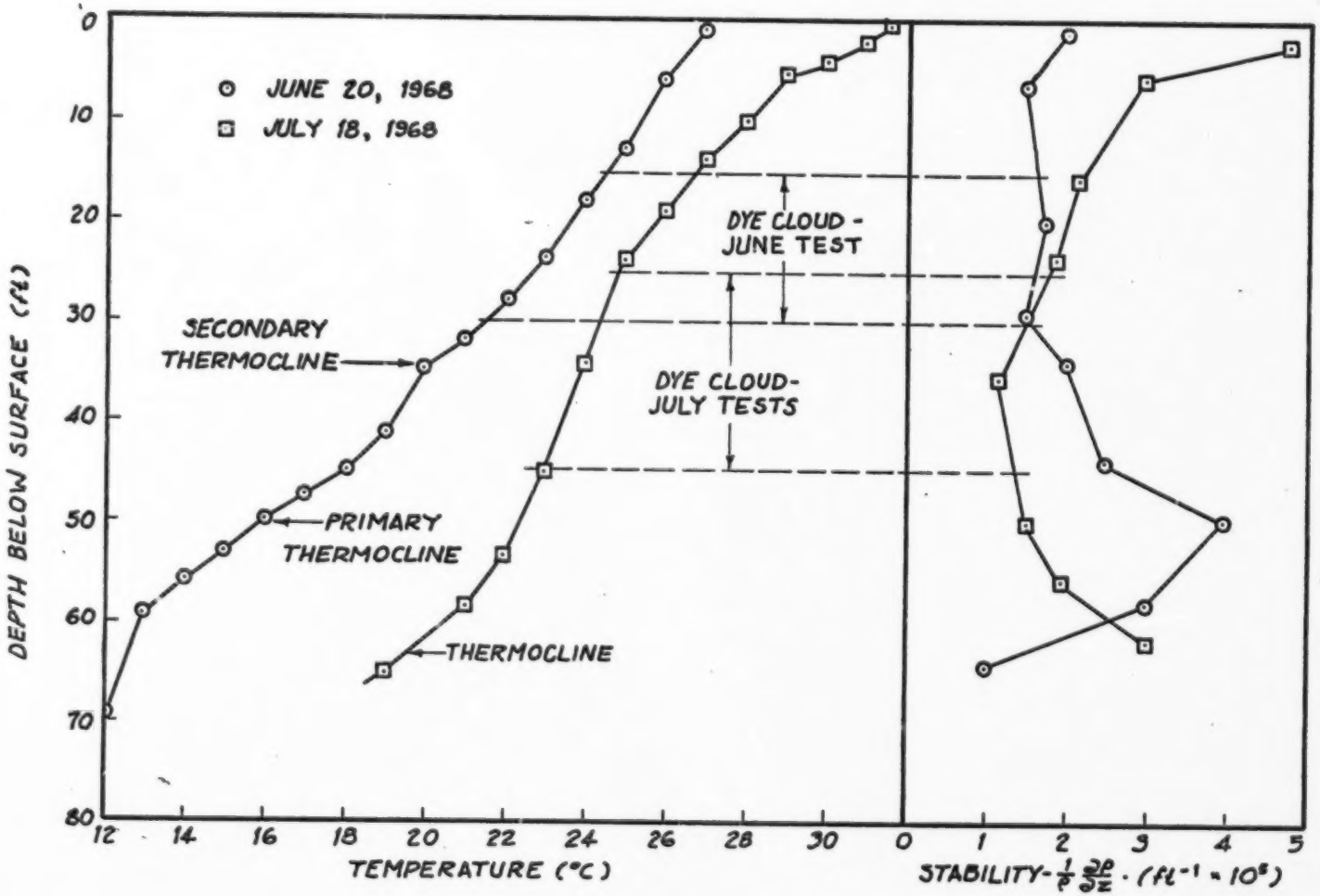


FIGURE 31 - TEMPERATURE AND STABILITY PROFILES

HRM 96.0, HRM 90.0, and HRM 84.0 for the June test are shown in Figure 32.

The longitudinal dispersion coefficients were estimated by both fitting the observed data to the conservation equation (Equation 7) and calculating the change of variance with respect to time (Equation 8). The longitudinal dispersion coefficients were estimated by the conservation equation to be 3800 ft^2sec^{-1}, 980 ft^2sec^{-1}, and 590 ft^2sec^{-1}, respectively. The average velocities in the respective reaches were estimated to be 0.55 ft sec^{-1}, 0.11 ft sec^{-1}, and 0.16 ft sec^{-1}. Since the dye injection was continuous for six hours, instead of instantaneous, the dispersion coefficients were overestimated with the greatest error occuring at the stations with the shortest average residence time. However, the predicted D_L for the station at HRM 84.0 whould be approximately correct since, according to Hays (7), an injection may be treated as instantaneous when the average residence time is about 20 or more times greater than the injection time.

The average D_L was determined by the change in variance with respect to time to be 360 ft^2sec^{-1} (Figure 33). This method for calculating D_L is not influenced by the dispersion of dye that occurred before the dye entered the reservoir, and it is, therefore, more indicative of the mixing occurring in stratified interflow than the preceding method.

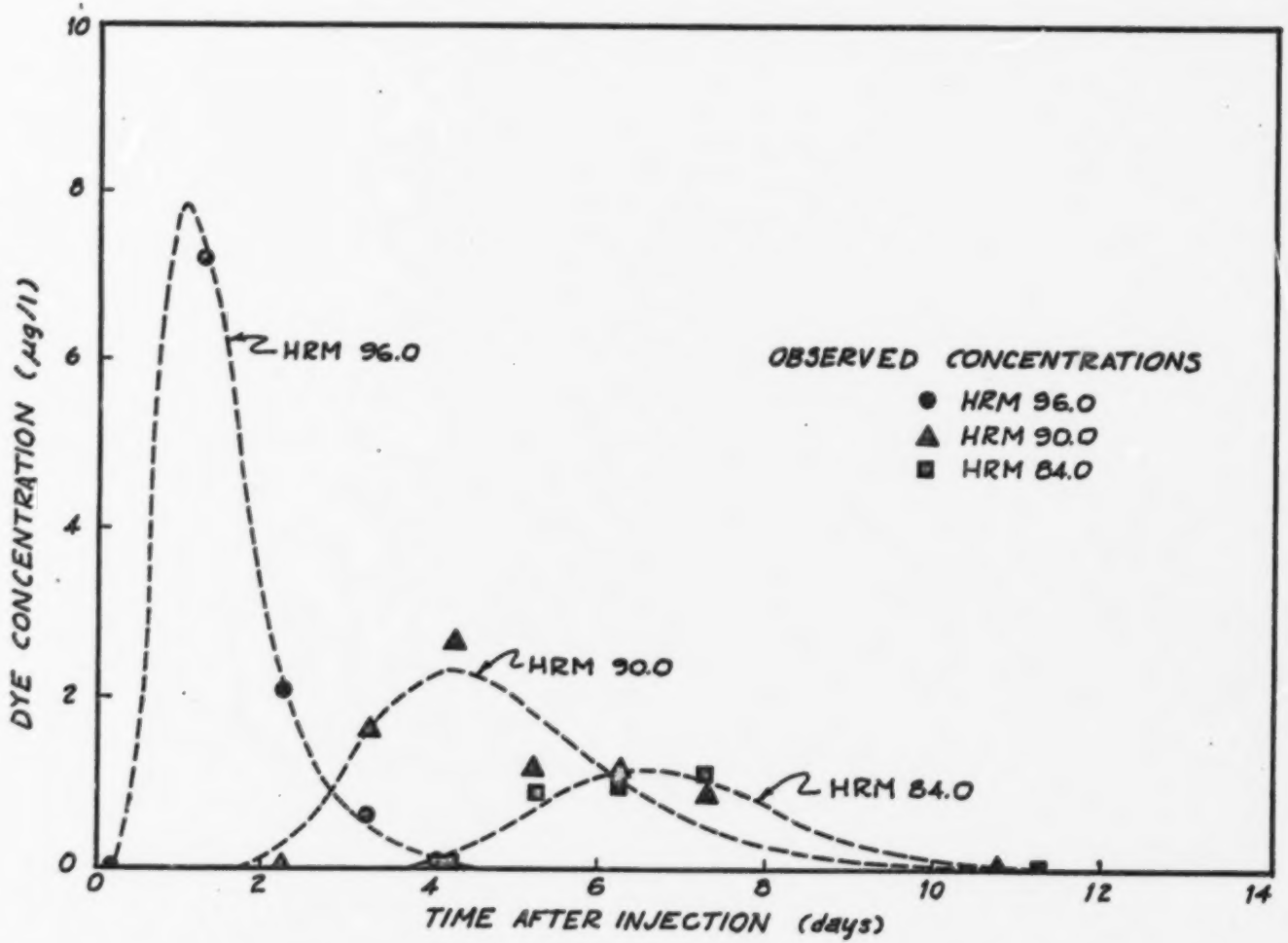


FIGURE 32 - DYE CONCENTRATION vs. TIME - JUNE TEST

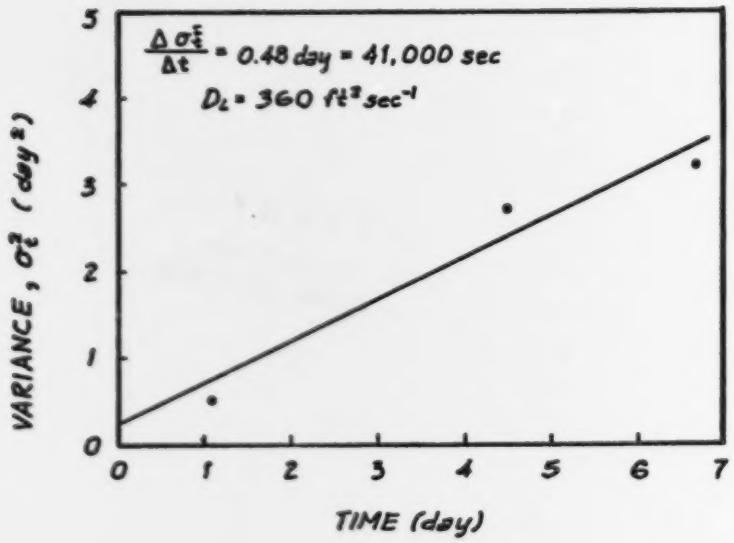


FIGURE 33 - CALCULATION OF D_L BY THE CHANGE OF VARIANCE